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Purchase or generate? An analysis of energy consumption, co-generation and substitution possibilities in energy intensive manufacturing plants under the Japanese Feed-in-Tariff

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Abstract

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Keywords: Renewable levy; Energy-intensive industry; Interfuel substitution
JEL Classification codes: Q41; Q48; L60; D24

1. Introduction

The 2011 Tohoku earthquake and tsunami that hit the Pacific coast on March 11th led to a sudden drop in electricity supply, and marks the beginning of an energy crisis in Japan.

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Nuclear power, which used to represent 11.2% of Japan's primary energy supply in 2010, dropped to 2.8% in 2018. The country's self-sufficiency ratio was halved and reached its lowest point of 6.4% in 2014. Suppliers were forced to turn to fossil fuel for power generation, increasing Japan's reliance on energy imports and the carbon intensity of the production. To solve the issue, the country introduced a Feed-in-Tariff (FIT) policy in July 2012, promoting domestic production of electricity through renewable energy sources. The policy resulted in a rapid expansion of solar power, growing roughly by 18% each year since 2012. The policy is financed by a renewable levy, similar to an electricity tax, proportional to electricity consumption and paid by all the consumers, including electricity consuming firms. With a fast increase of the tax rate over the years, the burden on end-consumers has also been rapidly increasing. In FY2020, it is estimated that households pay 774 JPY due to the costs of the levy[3].

While the energy crisis affected the Japanese economy as a whole, energy intensive (EI) manufacturing sectors were especially vulnerable. Following the earthquake, the government called for industrial sectors to voluntarily reduce their demand for electricity, so as to reduce the stress on the grid. Plants located in the Kanto and Tohoku areas also experienced rolling blackouts on a regular basis. Government called for plants with generation capacity to assist the main power companies. Some of the largest petrochemical plants in the country, located in industrial complexes of Kawasaki or Chiba and the Tohoku region, halted production entirely, affecting the downstream supply for the automobile and digital household appliances[4]. Large companies tried to cope by organizing emergency supply of gas and gasoline to their northeastern plants, or simply by shifting the production to the western part of the country. The aftermath of the shock did not bring much relief to the industry. While power supply stabilized, electricity prices increased by 38%, between 2010 and 2014, due to natural gas price movements and the introduction of the renewable levy. Calls for assistance of the manufacturing sector in electricity supply were still maintained, and manufacturers were encouraged to generate their own electricity. While March 11th was a shock for the industrial sector, policies implemented in its aftermath very much encouraged manufacturers to produce their own power, through FIT subsidies for renewable energy or subsidies for the installation of Combined Heat and Power (CHP) generators and energy efficiency equipment.

In this research, we focus on the changes in energy consumption in the aftermath of March 11th in plants belonging to EI sectors. Specifically, we examine how the plants mitigated the energy crisis and how their energy consumption changed due to the exogenous increase in electricity prices brought by the FIT levy. We focus on one mitigation method in particular, that is, whether EI plants attempted to substitute

[3] https://www.enecho.meti.go.jp/en/category/brochures/pdf/japan_energy_2020.pdf
[4] https://www.mlit.go.jp/common/001114055.pdf

electricity purchased from the market with electricity generated on site, and calculate the resulting emissions from this possible mitigation method.

We contribute to a growing body of literature on the impact of environmental policies and carbon pricing instruments on the manufacturing sector. Most studies evaluated the introduction of carbon taxation (Martin et al., 2014; Ordonez & Souza, 2022), Emission Trading Scheme (ETS) (Colmer, 2020; Martin et al, 2016; Petrick & Wagner, 2014), or general taxation system reform resulting in higher energy prices (Brucal & Dechezlepretre, 2021; Flues & Lutz, 2015; Marin & Vona, 2021; Morley, 2012). Despite differences in policy targets, all studies quoted above reach a consensus in that carbon pricing instruments (even implicit pricing) reduce pollution, though the extent of emission reduction is subject to debates. Emission reduction are often attributed to cleaner fuel or cleaner technology usage, leading to a reduction in emission intensity (Colmer, 2020; Morley, 2012; Ordonez & Souza, 2022). On the other hand, most studies on the manufacturing sector find little evidence of adverse economic effects, whether on output, employment or productivity (Brucal & Dechezlepretre, 2021; Flues & Lutz, 2015; Martin et al., 2014).

The hypothesis of substitution between energy inputs among plants of the manufacturing sector has been studied by Joskow (1984) and was followed by empirical study by Dismukes & Kleit (1999) and Hester & Gross (2001). However, following the rises in energy prices and the electrification of the manufacturing sector in recent years, the topic is resurfacing in the literature. The substitution hypothesis is usually explored through the evaluation of cross-price elasticity among the fuels and is still debated among scholars. Some studies confirm the substitution possibility with positive and significant cross-price elasticity (Bardazzi et al. 2015), usually with macro-level data (Hattori, 2008; Kabe, 2019; Serletis et al, 2010). Recent studies using plant-level information tend to reject the hypothesis (Kitamura & Managi, 2016), deem it as marginal in the total energy consumption of the plant (Lin & Li, 2016) or sector-dependent (Moller, 2017). The closest studies to ours relate to the exploration of this hypothesis in relation with carbon pricing instruments. Using plant-level data, these studies confirm the existence of substitution because of the introduction of a carbon tax (Dussaux, 2021), electricity tax due to changes in network charges (von Graevenitz & Rottner, 2022) or FIT levy (Lehr, 2022). On the other hand, Curtis & Lee (2019) refute the hypothesis that ETS or command and control regulations result in a higher share of electricity generated on site.

Our contribution is threefold. First, we examine the validity of the substitution hypothesis using plant-level data in the Japanese case by using two different indicators: cross-price elasticity and the share of electricity generated on site. Second, our study explores the mechanisms behind interfuel substitution, by analyzing cogeneration inside plants, by sector and by fuel type. Finally, our study uses exogenous variation in the FIT levy price thanks to the existence of an exemption system to provide a more precise identification of the effect of the levy. Our results show that a 1% increase in the levy rate results in a decrease in energy consumption, estimated to be around 3,800 tCO_2e per plant on average. We also confirm the substitutability between fossil fuel and electricity, as we showed that a 1% increase in the levy leads to an increase in 0.03pp in the share of electricity generated on site. We identify plants from the chemical sector as those with substitution capacity, and that the substitution leads to increased coal and gas consumption. While our study confirms the substitutability between the two energy inputs, its estimated magnitude is shown to be marginal.

The study is organized as follows: section 2 provides a literature review of the substitution mechanisms inside EI manufacturing plants. Section 3 describes the data and the identification strategy used in this study. Section 4 shows the estimation results and Section 5 displays results of calculations of resulting CO_2 emissions. Section 6 concludes this study.

2. A review of substitution mechanisms in EI manufacturing plants

2.1 Substitutability between fossil fuel and electricity as material input

Research on the topic of decarbonization of EI industry also thus flourished in recent years, and include several analysis of potential substitution technologies of fossil fuel as a material input. For instance, Garcia-Olivares (2015) provides a detailed review of the fossil fuel needs for each energy intensive industries.
In the case of iron and steel plants, Fan and Friedmann (2021) distinguish three different processes for steel production: blast furnace or basic oxygen furnace (BF-BOF) almost fully relies on coal; electric arc furnace (EAF) which can use electricity as an alternative to coal; and direct reduced iron (DRI), which does not necessitate the use of furnace but uses natural gas or coal in the reduction process (Fan and Friedmann, 2021). BF-BOF represents nearly 71% of global crude steel production and drives the demand of this sector for coke, used as reductant in the oxidation-reduction reaction (Fan and Friedmann, 2021). EAF is mostly used for producing recycled steel, and represent 24% of global steel production, but, due to its need for steel scraps as basic input, cannot fully replace BF-BOF as dominant process (Fan and Friedmann, 2021).

Regardless of the output, many chemical factories must rely on naptha or coal for conventional production (Garcia-Olivares, 2015). However, there is a possibility to electrify some portions of the production, for instance, through electrochemistry rather than petrochemistry (Schiffer and Manthiram, 2017). In this process, electricity can be used as a replacement for thermochemical methods, which necessitates high amount of heat, and drive chemical reactions at relatively low temperature (Schiffer and Manthiram, 2017). Authors show that such procedure can be used for ammonia, but similar process may also be applied for the production of methanol or ethylene (Schiffer and Manthiram, 2017). Still, Garcia-Olivares (2015) maintains that basic input for production (naptha) is still necessary, although it can be replaced with lower carbon alternatives such as charcoals, or by using biological substitutes for fossil fuel (Garcia-Olivares, 2015). If solutions exist for decreasing the role of fossil fuel in production, it would seem that they still remain in pioneering stages, and are not widely spread in the current production lines.

Regarding pulp and paper production, there seems to be a high level of substitutability between fuel (excluding wood) and electricity for producing steam necessary for the production process, which is mostly used in drying (Rahnama Mobarakeh et al., 2021). For instance, Garcia-Olivares (2015) suggest that no production process require fossil fuel per se, and the entirety of the production line could be electrified in the future. Still, Rahnama Mobarakeh et al. (2021) highlights that pulp and paper require energy for steam generation, for which fossil fuel is needed, as a more efficient input. However, in recent years, this particular industry has striven to replace fossil fuel with renewable energy or biofuel in order to reduce emissions in Austria (Rahnama Mobarakeh et al, 2021).

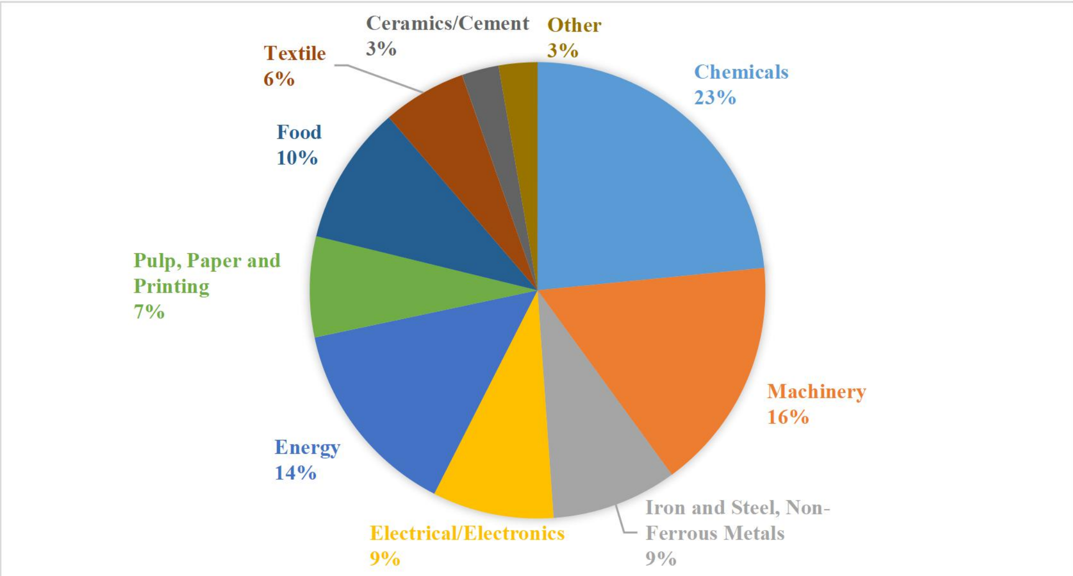
Overall, this section highlights that, in order to substitute fossil fuel (as material input) with electricity, a plant would require some heavy technological investment to replace their existing equipment, and that many processes that allow for such substitution are still in pioneering stages. Hence, in the few months that followed the Fukushima nuclear disaster, it is unlikely that plants were capable of substituting electricity with fossil fuel in the material process, as a response to tighter power supply and price spikes.

2.2 Substitution through onsite electricity generation

In this study, we focus on another potential source of substitution: we posit that plants facing relatively high electricity prices may have attempted to replace electricity purchased from the market with electricity generated on site. This section describes the production technology behind power generation inside EI manufacturing plants, and is partially based on interviews conducted with plants from the chemical, petrochemical, iron and steel sectors between March 2022 and January 2023.

A first method to generate electricity inside EI plants is through cogeneration or combined heat and power (CHP). This is a common practice among many sectors that require both energy and heat or steam in production, as CHP can provide both at the same time. Figure 1 below shows the share of each major industrial sector in the total electricity produced through CHP. Apart from the energy sector, we can see that the chemical sector and machinery sectors are the main electricity producers through CHP, followed closely by iron, steel and non-ferrous metals and electronics or electrical equipment. Since we focus on iron and steel and chemicals, we provide more details on the generation methods for these two sectors. CHP generation in the chemical sector occurs through fossil fuel-powered boilers, using waste gas and heat from the production process. In Japanese plants, coal or LNG are mostly used to power these boilers. Then, electricity and steam are produced through steam turbines. Recent attempts to reduce GHG emissions have resulted in chemical plants using gas turbines and waste heat boilers (powered by waste water) for CHP as well. CHP is preferred by petrochemical plants as it requires the same material input (coal, LNG) as the production process, and generally, electricity produced from CHP is cheaper than that of the market. Similar process is used in the iron and steel sector, using recovered heat from coke ovens and BF-BOF to power electricity and steam turbines. Interviews with plant managers revealed that electricity generated on site is far cheaper than purchasing it from power companies, due to the use of byproducts already present in the plant. However, for both chemical and iron & steel sectors, the amount of electricity produced through CHP cannot entirely cover the plants' energy needs, so the remaining amount is purchased through power companies. Interviews with managers showed that roughly half of respondents whose plants is equipped with CHP believe that an increase in electricity or fuel price would have a great impact on their production (Ida & Kinoshita, 2007).

Figure 1. Share each sector in total electricity generated through CHP



Source' authors' compilation, based on data from ACEJ (2023).

The majority of electricity produced by the pulp and paper sector, on the other hand, does not come from CHP but from thermal generation and biomass. Integrated paper mills producing pulp from wood chips have a large amount of waste material that can be used in biomass waste or black liquor boilers. In addition, paper plants may also have

CHP or fossil fuel-powered boilers. In the case of the paper industry, the main fuel input for boilers remains coal (26.2% of total energy consumption), followed by natural gas (6.3%) and heavy oil (5.5%)[5]. It is common for integrated paper mills to be nearly fully or fully independent when it comes to their energy needs. Overall, purchased power solely represents 8.4% in the total energy consumption of paper plants. Thus, paper plants were not as affected in the aftermath of March 11th as other sectors. In fact, since the FIT policy covers electricity produced from biomass, pulp and paper plants have gained a new incentive to sell their additional electricity to the grid. Through their interviews, Ida and Kinoshita (2007) showed that this production channel is not sensitive to changes in energy prices: 69.9% and 71.3% of respondents said their electricity generation using byproducts and waste would not be affected by a 10% increase in electricity or fuel prices, respectively.

In addition to CHP or thermal generators, some plants have also installed renewable energy installations. For instance, Tokyo Steel installed some solar panel in its Utsunomiya and Kitakyushu plants in 2020[6]. Chemical and petrochemical firms such as ENEOS or Mitsui Chemicals are also reported to have installed solar PV on rooftops of factories or remaining available space. Electricity can be sold back to the grid at a relatively high price, but some chemical companies are considering installing renewable energy to produce green hydrogen in an attempt to decarbonize their production line. Once installed, however, renewable energy production is not easy to forecast, thus, it is unlikely that substitution attempts could come from this channel.

Interviews inside the plants and a review of the generation systems installed inside Japanese plants showed that substitution could occur if energy prices were to rise. However, not every generation channel can provide this mitigation method, as only CHP and thermal generation offer enough leeway in the generation amount. Other method (byproduct gas, renewable energy, waste material) largely depend on manufacturing production or weather variations, which are not easily adjustable[7]. Any adjustment to replace purchased power must therefore be powered with fossil fuel, hence, we extent our analysis to fossil fuel used to power CHP generators, in addition to electricity generated on site.

3. Methodology

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[5] https://www.meti.go.jp/shingikai/enecho/denryoku_gas/denryoku_gas/sekitan_karyoku_wg/pdf/003_07_00.pdf

[6] https://project.nikkeibp.co.jp/ms/atcl/19/news/00001/01170/?ST=msb

[7] The majority of renewable installations approved under the FIT program are intermittent renewable energy such as solar or wind in Japan. A minority of plants may also generate energy through small to medium-scale hydropower.

3.1 Data

In this paper, we use data from the current survey of energy consumption (CSEC), which provides information on monthly consumption of Japanese plants belonging to EI sectors from 2005 to 2018. The CSEC survey is also used by Kitamura & Managi (2016) and Mortha et al. (2022) in their studies of Japanese EI industries. The survey provides very detailed description of energy consumption inside plants: it contains the quantity of fuel, electricity and steam consumed for each month, and the plant also describes the usage target of each energy input. Using this survey, we can calculate how much fossil fuel was used to power CHP and other thermal generators. This particular indicator is crucial to evaluate whether the substitution hypothesis holds, as Section 2 showed that only CHP and thermal generators (powered by fossil fuel) offered enough flexibility for plants to adjust their electricity generation. Building on the works of Curtis & Lee (2019) and Kabe (2019), the key indicator to identify whether substitution occurs is vertical integration, a variable indicating the share of electricity generated on site, as a total of electricity consumed inside the plant. A similar variable was constructed for fossil fuel, representing the share of fossil fuel used to generate power inside the total fossil fuel consumption of the plant.

While the levy rate is determined exogenously in each year, its effects on energy consumption may depend on relative energy prices, hence we also include electricity and fossil fuel prices. As a proxy for fossil fuel price, we use diesel prices, for large industrial consumers. They are available on a monthly and regional basis from 2003 (Agency for Natural Resources and Energy, 2023). Since all diesel in Japan is practically imported from abroad, fluctuations in diesel prices reflect broader fluctuations of other fossil fuel prices. Previous studies also used aggregate electricity price provided by the 10 regional monopolistic power companies (Kabe, 2019; Kitamura & Managi, 2016), which was retrieved as well. However, interviews with power plant managers revealed that many of them switched electricity provider, making use of the liberalization of the electricity market since the early 2000s[8]. To reduce endogeneity concerns, we use regional electricity spot market price provided by the Japan Electric Power Exchange (JEPX), and aggregate the hourly data to average monthly values (JEPX, 2023).

Finally, we need to control for the plant characteristics that could affect its demand for electricity, as well as the amount of power generated on site. To this end, we use the number of employees inside the plant, which was retrieved from Pollutant Release and Transfer Register (PRTR) publicly available from METI (2020). We also control for the firm's production by using firm sales and the rate of return on equity, both available from Toyo Keizai database (Toyo Keizai, 2020). Since the 2010 and 2011 respectively,

[8] Full liberalization of the Japanese electricity market occurred in 2016, but large electricity consumers (demand above 500kW) have been able to freely choose their electricity retailer since 2004.

Tokyo and Saitama prefectures have introduced a local ETS scheme, which may affect the energy demand inside the plants, hence, we also add a Tokyo and Saitama ETS binary variable to capture this effect. The list of targeted plants is available on each prefectural government website (Saitama Prefectural Government, 2021; Tokyo Metropolitan Government, 2021).

3.2 Identification strategy

The main objective of this research is to identify the effects of the FIT policy. A usual approach taken in the literature is a Difference-in-Differences (DID) model. The effects of the policy are captured by a treatment dummy variable, taking the value 1 after implementation (Dong, 2012; Jenner et al., 2013; Kilinc-Ata, 2016; Taghizadeh-Hesary et al., 2020). In the case of FIT, since the levy rate changes each fiscal year and is applied uniformly across the country, this treatment variable would become a year fixed effect. This is especially problematic in Japan because the introduction of FIT in 2012 came in the aftermath of March 11th, an event that caused long-lasting changes in energy demand. A year fixed effect would likely capture many other factors affecting manufacturing plants' energy demand after 2012[9].

This concern is not specific to Japan, however, as many empirical economists attempting to evaluate carbon pricing policies face similar identification issue. If the policy only targets a selected number of plants or sub-national division, identification can be realized with a DID estimator or with a synthetic control method. Examples of such study is Yamazaki (2017) or Leroutier (2022). Another common identification method consists in taking advantage of partial tax exemptions or discounts offered to EI industry. This method of identification is used by Martin et al. (2014) in the case of the United Kingdom's climate change levy, or by Flues &Lutz (2015) and Gerster & Lamp (2020) in the case of the German FIT levy.

This study makes use of a similar exemption system, offered to plants with large electricity consumption and a high energy intensity. For a detailed description of the eligibility conditions of the scheme, we refer the reader to Mortha et al. (2022). Under this system, plants can receive up to 80% discount on the FIT levy. After a reform of the scheme in 2017, eligible plants can receive 40% or 80% of discount on the levy, depending on their energy efficiency efforts. Using the list of exempted plants and the electricity consumption and intensity at the time of registration (Agency for Natural Resources and Energy, 2020), we can compute the effective rate of levy paid by each plant. Figure 2 below shows the evolution of the electricity prices paid by consumers, for each major electricity provider[10].

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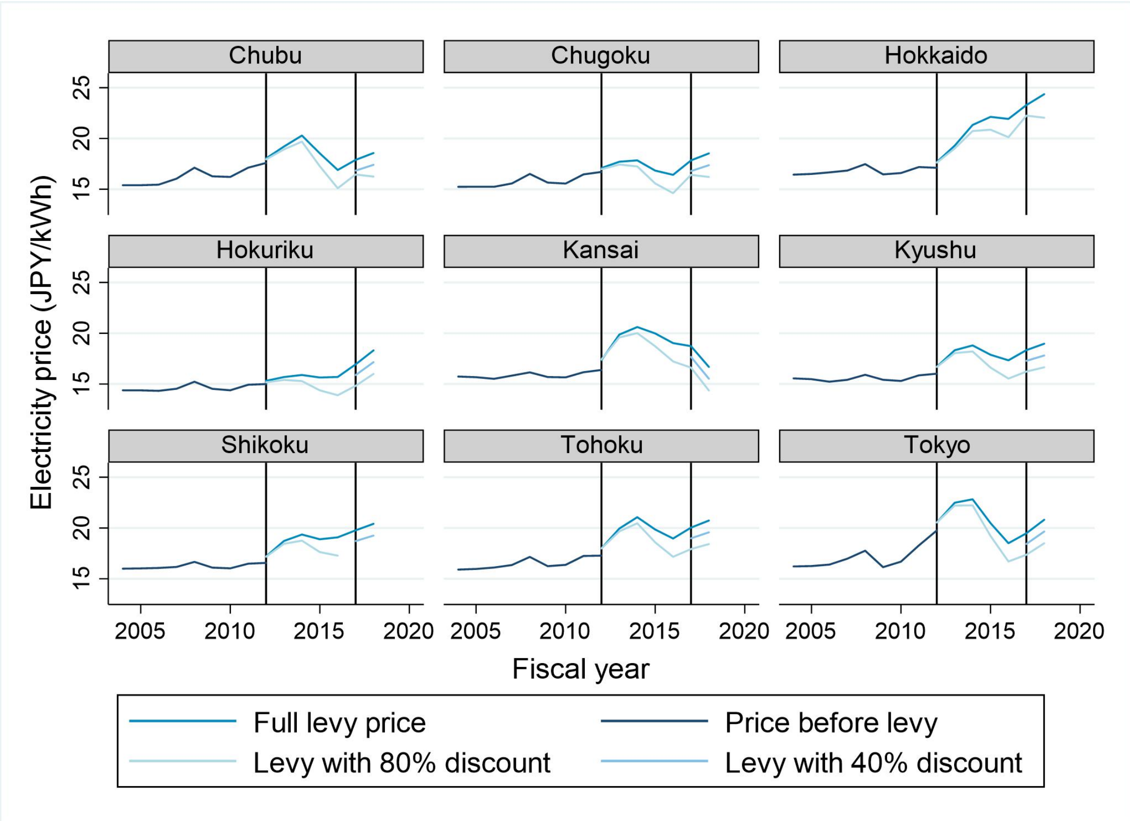
[9] Among these factors, we can think about the introduction of a carbon tax nationwide in 2012, although its rate is very low. In addition, the Fukushima nuclear disaster also resulted in many customers switching their electricity retailers from Tokyo Power Company. The resulting blackouts may have motivated manufacturing plants to conduct structural reforms and invest in new technology.

[10] Okinawa is excluded, as none of the plants in our sample are located in the area.

A general trend that appears is that electricity prices have greatly increased in the aftermath of March 11th, although some regions have taken a larger hit than others (Hokkaido, Tokyo, Tohoku, all located on the Eastern part), possibly due to the aftermath of the disaster and grid characteristics[11]. The aftermath of Fukushima also coincides with relatively low fossil fuel prices on the international market. Fossil fuel prices were especially low around 2015-2017, explaining the fall in electricity prices in all regions. Despite this price fall, it is interesting to note that consumers paying the full levy have been facing higher prices than before, while consumers receiving the discount may have experienced electricity prices that have been lower than those paid before March 11th (Chubu, Chugoku, Hokuriku, Kansai, all located on the Western part). High electricity prices in the 2012-2013 periods, coupled with relative low prices of fossil fuel, may have given an incentive to industrial producers to substitute electricity with fossil fuel.

Figure 2. Evolution of electricity rates by region



Source: authors' compilation based on aggregate electricity prices retrieved from the Federation of Electric Power Companies of Japan (2020), and calculated from each of the 9 major Electricity Power Companies, excluding Okinawa. Vertical lines are added to the fiscal year of introduction of the FIT levy

[11] East and West Japan are connected through a frequency converter between Tokyo and Chubu area, as East Japan grid is 50Hz while West Japan uses 60Hz. East Japan was most affected by supply chains disruptions but possibilities of sending electricity from the West was limited due to this infrastructure characteristic.

(2012) and to the year where the exemption system was reformed (2017).

After 2012 and the introduction of the levy, one can see that consumers can face different levy price, regardless of the region of location, based on their eligibility for the exemption scheme. Using these exogenous variation in levy prices, we construct a continuous levy variable, which captures the fluctuations in the tax rate, and use it to evaluate the effect of the levy on energy consumption inside plants.

To this end, we estimate the following model, written in equation (1):

$$y_{it} = \alpha + \beta_1 p_{it}^{e} + \beta_2 p_{it}^{ff} + \beta_3 levy_{it} + \theta X_{it} + \gamma_i + \varepsilon_{it} \qquad (1)$$

Where "y" is a dependent variable (energy consumption and components), "α" is a constant term, "p" refers to energy prices of electricity (subscript e) or fossil fuel (subscript ff) inside plant i at time t, "levy" is the variable of interest, capturing fluctuations in the levy rate inside plant i at time t, X is vector of covariates described in the previous section and a monthly fixed effect, γ is a plant fixed effect and ε is an error term.

Despite the use of covariates, it is very likely that there might be some unobserved factors that could affect energy demand inside the plant. Examples of such factors include the type of product manufactured by the plant, which is not described inside the survey, generation technology and efficiency, production efficiency among others. All of these unobserved factors could affect the plants' sensitivity to changes in energy prices, but cannot be included in the analysis per se. Therefore, we aim to estimate the equation above by adding a plant fixed effect (γ)[12].

3.3 Estimation method

Table 1 below provides the summary statistics for our main dependent variables, energy price and other control variables. We use two types of dependent variables: the absolute amount consumed inside the plant and the share this amount represents inside the total consumption of electricity or fossil fuel consumption (vertical integration). We look at the amount of electricity generated on site, fossil fuel consumed to power cogenerators[13], byproducts, coal, oil and gas that are used for electricity generation, as well as their respective share. For this study, we restrict our sample to plants with generating capacity[14]. After adding covariates, our sample contains, at most, 9,420 observations

[12] The use of a fixed effect implies that we assume that the unobserved factors are constant over time, within a given plant. Given that our sample runs from 2005 to 2018, this assumption may be a strong one, as the electricity supply disruption may have provided an incentive for plants to invest in new, energy-efficient equipment

[13] This particular variable only considers "non-process" fuels in the CSEC survey, that is, fuels that are not byproducts generated during production.

[14] Technology inside the plant, including whether the plant has generation capacity, is not available in the

across 99 plants. Among them, 44 belong to the chemical sector, 35 to the iron and steel sector and 20 to the pulp and paper sector, for a total of 4968, 2556 and 1896 observations per sector, respectively.

Table 1. Summary statistics

	Variable	Observations	Mean	Standard Deviation	Min	Max	Number of zero -valued obs.
Dependent variables: energy consumption	Electricity generation	9,420	5,938.86	10,095.02	0	83,327	2,329
	Fossil fuel for cogeneration	9,409	9,009.37	13,169.74	0	113,056.90	581
	Byproduct material consumption for generation	9,420	3690.76	9166.44	0	67280.10	6,569
	Coal consumption for generation	9,420	2481.36	6444.31	0	56866.68	7,557
	Oil consumption for generation	9,420	1276.72	3030.83	0	21652.83	5,066
	Gas consumption for generation	9,420	1224.01	2340.99	0	20212.69	4,328
	Energy consumption	9,420	62,967.36	143,787.90	0	1,089,702	7
Dependent variables: substitution indicators	Vertical integration (electricity)	9,403	0.27	0.40	0	2.77	2,312
	Vertical integration (fossil fuel)	9,408	0.44	0.30	0	1	580
	Vertical integration (byproduct)	9,408	0.04	0.09	0	0.56	6,557
	Vertical integration (coal)	9,408	0.05	0.13	0	0.69	7,545
	Vertical integration (oil)	9,408	0.08	0.17	0	0.98	5,054
	Vertical integration (gas)	9,408	0.15	0.23	0	0.91	4,316
Energy price	Electricity price (Spot market)	9,240	10.95	3.30	3.34	19.89	0
	Industrial diesel price	9,420	100.23	14.30	72.5	147.5	0
	FIT levy	9,420	0.51	0.87	0	2.9	5,193
Other control variables	Employees inside the plant	9,420	593.42	779.76	4	9,518	0
	Saitama ETS	9,420	0.01	0.11	0	1	9,312
	Tokyo ETS	9,420	0.01	0.11	0	1	9,312
	Return on Equity	9,420	0.23	4.49	-0.41	126	0
	Firm sales (log)	9,420	13.25	1.54	9.03	16.33	0

Source: authors' compilation. Figures are rounded to two decimals. Vertical integration is expressed in percentage, electricity generation is expressed in thousands kWh, and fossil fuel and energy variables are expressed in tCO_2e.

Despite restricting our population of analysis to plants with generating capacity, we still observe that a large number of of our dependent variables are zero-valued. For instance, roughly 80% of plants never use coal to generate electricity. This issue is especially

CSEC survey. However, provided that our sample period is sufficiently long (>10 years), we infer that plants that do not generate a single kWh of electricity during the study period do not possess generation capacity.

acute when we consider cogeneration by fuel, as this is directly linked with the plant's available technology. In the case of non-linearity of the dependent variable, the use of the traditional Ordinary Least Square (OLS) estimate is not advised, as it will suffer from a severe downward bias (Wooldridge, 2010). Transforming the dependent variable into their logarithmic form is also not recommended, as zero-valued observations will be dropped. In their application to trade data with many missing or zero-valued trade flows, Santos-Silva & Tenreyro (2006) showed that using Poisson Pseudo-Maximum Likelihood (PPML) estimator with robust (clustered) standard errors led to the most consistent estimator[15].

4. Empirical Results

4.1 Electricity production on site

The next section presents the estimated results of equation 1. We show the results for two dependent variables: total amount of electricity generated on site and the share of electricity generated on site inside total electricity consumption (vertical integration), presented in Table 2 and 3, respectively. We present only coefficients associated with the levy and energy prices, though full results are available in the appendices.

Table 2. Estimation results (vertical integration, electricity)

	All	Iron and Steel	Chemicals	Pulp and Paper
Method	PPML	PPML	PPML	PPML
FIT levy	0.02	-0.06	0.06	-0.09
	(0.05)	(0.09)	(0.08)	(0.06)
Electricity price	0.02*	1.75E-03	0.03*	1.21E-03
	(0.01)	(0.01)	(0.01)	(5.51E-03)
Diesel price	-2.81E-03*	-6.57E-03	-0.00201	-2.67E-03*
	(1.49E-03)	(5.44E-03)	(2.15E-03)	(1.52E-03)
Fixed effect	Month and plant			
Number of plants	91	32	42	17
Number of observations	8,894	2,380	4,821	1,693

Source: authors' compilation. Standard errors in parenthesis, clustered by plant. Results are rounded to two decimals. "*", "**" and "***" represent significance at 10%, 5% and 1%, respectively. For complete results, please check appendix A1.

Table 3. Estimation results (electricity generation)

	All	Iron and Steel	Chemicals	Pulp and Paper

[15] While Poisson is traditionally used for count data (non-negative integers) and data following a Poisson process, Santos-Silva & Tenreyro (2006), as well as Wooldridge (2010) show that the use of Poisson regression can be extended to non-Poisson data (as long as clustered errors are used) and non-integer data as well.

Method	PPML	NB2	PPML	NB2	PPML	NB2	PPML	NB2
FIT levy	0.02	-5.00E-03	0.02	0.19	0.05	-0.07	-0.07	-0.18
	(0.07)	(0.10)	(0.06)	(0.21)	(0.08)	(0.11)	(0.05)	(0.28)
Electricity price	3.09E-03	-0.03	3.79E-03	-0.03	7.40E-03	-0.04	6.13E-03	-0.06
	(0.01)	(0.02)	(0.01)	(0.04)	(0.02)	(0.03)	(4.63E-03)	(0.05)
Diesel price	-5.83E-04	5.57E-04	1.64E-03	3.83E-03	-1.10E-03	-4.46E-04	-2.75E-03	-5.99E-05
	(1.53E-03)	(3.94E-03)	(1.83E-03)	(0.01)	(2.20E-03)	(0.01)	(2.11E-03)	(0.01)
Fixed effect	Month and plant							
Number of plants	91	91	32	32	42	42	17	17
Number of observations	8,907	8,907	2,387	2,387	4,827	4,827	1,693	1,693

Source: authors' compilation. Standard errors in parenthesis, clustered by plant for OLS and PPML, and bootstrapped for NB2. Results are rounded to two decimals. "*", "**" and "***" represent significance at 10%, 5% and 1%, respectively. For complete results, please check appendix B1.

Regardless of the sector, it appears clearly that the levy did not raise the share of electricity generated on site or the total amount of electricity generated on site, a result that is fairly similar to Curtis & Lee (2019). Nevertheless, the energy price coefficients are marginally significant, and seem to indicate that substitution through cogeneration could occur: the positive sign associated with electricity prices suggest that a rise in electricity prices result in a higher share of electricity generation. On the other hand, we observe the opposite result for diesel prices, in line with the fact that fossil fuel purchased externally is the main input behind electricity generation.

We find little evidence of the sensitivity of the total amount of electricity generation to any form of energy price, including the levy. This particular result could be explained by the difference in production method used for power generation: while coal, oil or gas used for power generation could be affected to a change in energy prices, Ida & Kinoshita (2007) showed that CHP fueled by byproducts is not sensitive to electricity (or fuel) prices. However, one cannot identify such differences in production methods by looking at the amount of electricity generated as a whole.

4.2 Fossil fuel powering electricity generation

Given that many plants use different types of fuel for generation at the same time, we cannot easily distinguish between production methods by simply looking at the sheer amount of electricity generated on site. Instead, we analyze the changes in fossil fuel consumption reported to be used for electricity generation. Table 4 and 5 show the result of vertical generation estimates, by sector and fuel type, respectively.

Table 4. Estimation results (vertical integration for fossil fuel, by sector)

Fossil fuel for cogeneration (excluding byproducts, waste)	All	Iron and Steel	Chemicals	Pulp and Paper
Method	PPML	PPML	PPML	PPML
FIT levy	0.04**	-0.01	0.07***	-1.84E-03
	(0.02)	(0.05)	(0.03)	(0.01)
Electricity price	0.01	-4.04E-03	0.01	2.15E-03
	(4.73E-03)	(0.01)	(0.01)	(1.88E-03)
Diesel price	-9.52E-04*	-2.47E-03	-9.04E-04	-5.70E-04**
	(5.45E-04)	(4.26E-03)	(6.62E-04)	(2.68E-04)
Fixed effect	Month and plant			
Number of plants	95	31	44	20
Number of observations	8,716	1,971	4,887	1,858

Source: authors' compilation. Estimation method: Poisson Pseudo Maximum Likelihood (PPML). Standard errors in parenthesis, clustered by plant. Results are rounded to two decimals. "*", "**" and "***" represent significance at 10%, 5% and 1%, respectively. For complete results, please check appendix A2.

Once we remove the generation through byproduct and waste, results from Table 5 show that the coefficients associated with the levy are positive and significant, for all sectors overall, but this is especially true for the chemical sector. Given that nearly half of the plants in the sample, the chemical sector could be driving the results for the overall regression. The reduced number of observations for iron and steel and pulp and paper sector could also explain the lack of significance. As expected, diesel price, our proxy for fossil fuel prices, are shown to be negative and significant, especially in the case of the pulp and paper sector, but we fail to obtain significant results for electricity prices.

Table 5. Estimation results (vertical integration, by fossil fuel type)

Fossil fuel for cogeneration and boilers	Byproducts and waste	Coal	Oil	Gas
Method	PPML	PPML	PPML	PPML
FIT levy	2.75E-03	0.29*	-0.53***	0.10*
	(0.08)	(0.16)	(0.14)	(0.05)
Electricity price	-6.28E-03	-6.73E-03	-6.11E-04	5.47E-04
	(7.37E-03)	(0.01)	(0.02)	(0.01)
Diesel price	7.56E-04	3.34E-03**	-6.61E-03*	1.02E-03
	(2.00E-03)	(1.67E-03)	(3.78E-03)	(1.53E-03)
Fixed effect	Month and plant			

Number of plants	33	21	62	61
Number of observations	3,209	1,992	5,727	5,881

Source: authors' compilation. Estimation method: Poisson Pseudo Maximum Likelihood (PPML). Standard errors in parenthesis, clustered by plant. Results are rounded to two decimals. "*", "**" and "***" represent significance at 10%, 5% and 1%, respectively. For complete results, please check appendix A3. Categories are not mutually exclusive: plants using byproduct fuels can also use gas for instance.

Table 5 shows the estimation results when we divide fossil fuel consumption by fuel category for generation. As Ida & Kinoshita (2007) and our more recent interviews reflected, the share of byproduct and waste to power generation is not sensitive to changes in energy prices, including the levy. On the other hand, we see that higher levy price increases the share of coal and gas used for generation inside the total fossil fuel consumption of the plant, reflecting that substitution is possible to an extent, and that said substitution would indeed be coming from fossil fuel purchased from the market. The size of sub-sample is also interesting to note, as there are many plants using oil or gas (roughly 60% of the sample) while only a handful utilize coal for cogeneration (around 20% of the sample).

Table 6. Estimation results (fossil fuel for cogeneration)

	All		Iron and Steel		Chemicals		Pulp and Paper	
Method	PPML	NB2	PPML	NB2	PPML	NB2	PPML	NB2
FIT levy	-0.05*	-0.05*	-0.25 ***	-0.13	-0.01	-0.03	-0.14 **	-0.08
	(0.03)	(0.03)	(0.06)	(0.13)	(0.03)	(0.03)	(0.07)	(0.05)
Electricity	-0.01**	-3.58E-03	-0.01	-0.01	-2.90E-03	-1.71E-03	-4.01E-03	4.05E-03
price	(4.15E-03)	(4.81E-03)	(0.01)	(0.02)	(2.86E-03)	(6.52E-03)	(0.01)	(0.01)
Diesel price	-1.12E-03	-9.65E-04	-3.24E-03	-404E-03*	-4.16E-04	-1.03E-03	-0.00102	-4.07E-04
	(6.95E-04)	(9.18E-04)	(2.79E-03)	(2.16E-03)	(7.72E-04)	(9.60E-04)	(0.00113)	(1.41E-03)
Fixed effect	Month and plant							
Number of plants	95	95	31	31	44	44	20	20
Number of observations	8717	8717	1972	1972	4887	4887	1,858	1,858

Source: authors' compilation. Standard errors in parenthesis, clustered by plant. Results are rounded to two decimals. "*", "**" and "***" represent significance at 10%, 5% and 1%, respectively. For complete results, please check appendix B2.

Tables 6 and 7 show us the effects of changes in energy prices on the amount of fossil fuel consumed, by sector and by fuel type, respectively. Overall, we can see that the levy reduces consumption of fossil fuel overall, which is driven by a decrease in consumption of oil, byproduct and waste. Given that the latter are generated during production, this result might reflect that the levy has adverse effects on production inside the plants.

Table 7. Estimation results (fossil fuel consumption for boiler and cogeneration, by fuel type)

	Byproduct and waste		Coal		Oil	Gas	
Method	PPML	NB2	PPML	NB2	PPML	PPML	NB2
FIT levy	-0.13***	-0.35***	0.03	-0.02	-0.31**	-0.01	0.15
	(0.05)	(0.12)	(0.04)	(0.04)	(0.14)	(0.12)	(0.11)
Electricity price	-4.18E-03	-0.02	6.27E-04	-0.02	-0.01	-3.49E-04	3.56E-03
	(0.01)	(0.03)	(3.87E-03)	(0.01)	(0.01)	(0.02)	(0.02)
Diesel price	-4.74E-04	1.77E-03	5.37E-04	2.80E-03	-0.01***	1.35E-03	1.02E-03
	(1.16E-03)	(4.11E-03)	(6.66E-04)	(2.61E-03)	(2.06E-03)	(1.85E-03)	(3.59E-03)
Fixed effect	Month and plant						
Number of plants	33	33	21	21	62	61	61
Number of observations	3,209	3,209	1,992	1,992	5,727	5,888	5,888

Source: authors' compilation. Standard errors in parenthesis, clustered by plant. Results are rounded to two decimals. "*", "**" and "***" represent significance at 10%, 5% and 1%, respectively. For complete results, please check appendix B3. "Byproduct and waste" include gas from coke oven, blast furnace and converters, hydrocarbon reported as byproducts (oil or gas), recovered black liquor and waste material. "Coal" includes coal, coal coke and petroleum coke. "Oil" includes kerosene, diesel, naphtha, heavy and crude oil (excluding NGL). "Gas" includes LPG, LNG, piped gas, NGL and condensate and natural gas.

4.3 Total energy consumption

Finally, we analyze the overall effect of the levy on energy consumption inside plants. Results of this regression are presented in Table 8.

Table 8. Estimation results (energy consumption)

	All		Iron and Steel		Chemicals		Pulp and Paper	
Method	PPML	NB2	PPML	NB2	PPML	NB2	PPML	NB2
FIT levy	-0.06	-0.08**	-0.09*	-0.11	-0.06	-0.08**	-0.13**	-0.07
	(0.05)	(0.03)	(0.05)	(0.07)	(0.07)	(0.03)	(0.06)	(0.04)
Electricity price	-3.91E-03	-4.37E-03	4.74E-03	0.01	-0.01	-0.01**	-2.96E-03	2.68E-03
	(4.69E-03)	(4.54E-03)	(4.42E-03)	(0.01)	(0.01)	(4.43E-03)	(0.01)	(0.01)
Diesel price	6.02E-04	6.94E-04	-1.08E-03	-2.50E-03*	1.97E-03 **	1.52E-03 **	-6.68E-04	1.40E-04

	(6.98E-04)	(6.31E-04)	(1.57E-03)	(1.51E-03)	(9.95E-04)	(7.22E-04)	(9.53E-04)	(1.27E-03)
Fixed effect	Month and plant							
Number of plants	99	99	35	35	44	44	20	20
Number of observations	9,240	9,240	2,495	2,495	4,887	4,887	1,858	1,858

Source: authors' compilation. Standard errors in parenthesis, clustered by plant. Results are rounded to two decimals. "*", "**" and "***" represent significance at 10%, 5% and 1%, respectively. For complete results, please check appendix B4.

Results from table 8 confirm previous results, as it shows that the levy has a negative effect on energy consumption as a whole, regardless of the sector. This result could reflect the adverse effects of the tax on production as well, given how essential energy (electricity, steam and fossil fuel) is in the production process in EI industries. Alternatively, it is also possible that the reduction in energy consumption could reflect improvement in energy efficiency, to an extent. Unfortunately, we do not have data on production at the plant level, to confirm the explanation above, and elucidate which effect (production reduction or efficiency gains) is dominant.

5. Simulation of resulting CO_2 emissions

While the levy acted as an incentive to reduce electricity consumption, our results show that it also increased the share of fossil fuel consumption for cogeneration. To an extent, it might have encouraged further fossil fuel consumption, leading to additional CO_2 emissions. Therefore, this section uses our estimates to compute the emissions associated with the introduction of the levy. To this end, we predict the values of each of our dependent variables if the levy had been zero, according to equation 2.

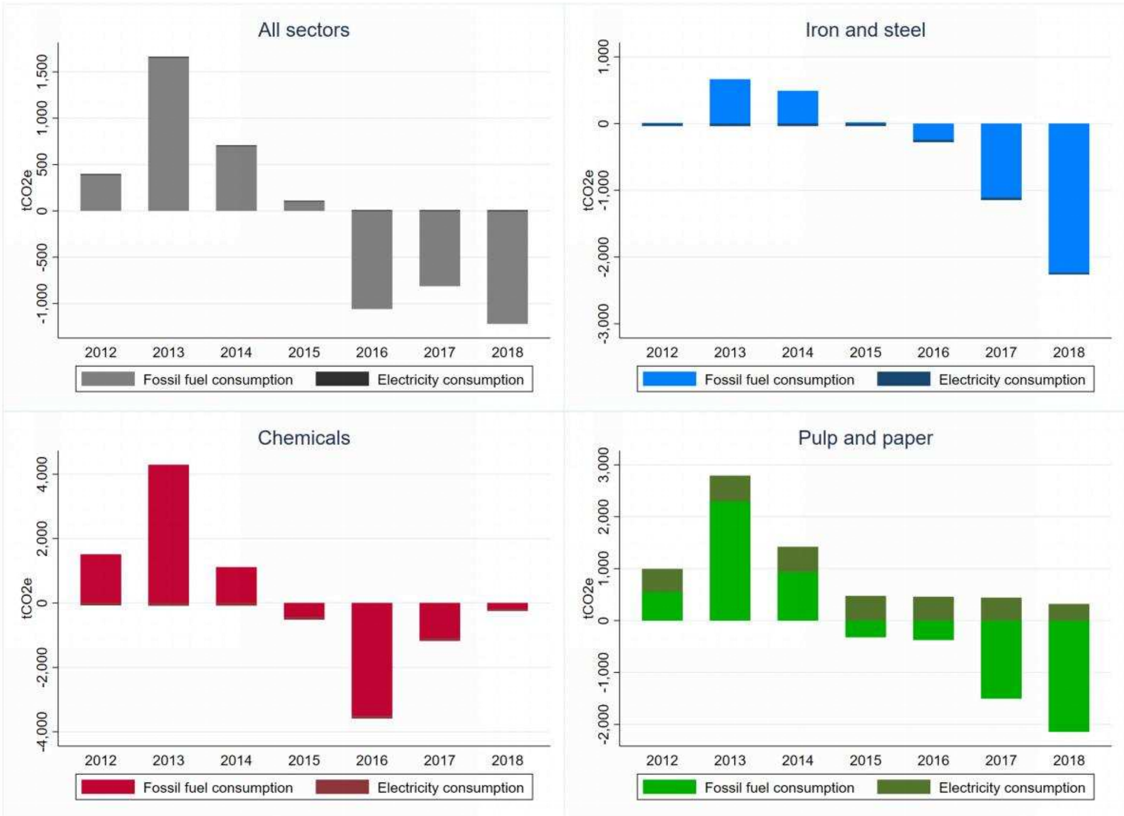
$$\hat{y}_{it} = \alpha + \beta_1 p^{e}_{it} + \beta_2 p^{ff}_{it} + \beta_3 levy \times 0 + \theta X_{it} + \gamma_i + \varepsilon_{it} \quad (2)$$

Then, we obtain simulated values (equation 3) of our dependent variables by subtracting the predicted values to the observed values of the variable. The simulated values should be understood as the average effect of the levy on each dependent variable.

$$y^{SIM}_{it} = y_{it} - \hat{y}_{it} \quad (3)$$

The resulting dependent variables are averaged by fiscal year, and presented in the figures below. To ease the comparison, we convert electricity consumption into tCO_2e. The complete conversion methodology is described in appendix 3. First, Figure 3 shows the effect of the levy on electricity and fossil fuel consumption, by sector and fiscal year. Clearly, from Figure 3, we can see that the reduction in emission associated with the decrease in electricity consumption is very small, compared to emission due to fossil fuel consumption (with the exception of the pulp and paper sector). Then, we see a rebound in fossil fuel consumption in the first few years after the levy was introduced. This rebound is especially pronounced for the chemical and pulp and paper sector. The rebound does not last, however, and emission from fossil fuel is shown to be decreasing as the levy rate increases. One possible explanation could come from attempts to substitute electricity in the first few years, as the levy was sufficiently small so that the fall in purchased electricity could be compensated by a slight increase in electricity generated on site. As our results show, however, the magnitude of the substitution is rather small, and hence, as the rate of the levy rose, it became increasingly difficult to substitute the purchased electricity entirely, and plants eventually reduced their consumption of fossil fuel altogether. It is also interesting to note that the pulp and paper industry actually increases its electricity consumption. Since we reduced our sample to plants with generating capacity, we are likely analyzing integrated pulp plants, whose electricity consumption is mostly coming from on site generation, and thus, is not as affected by the levy.

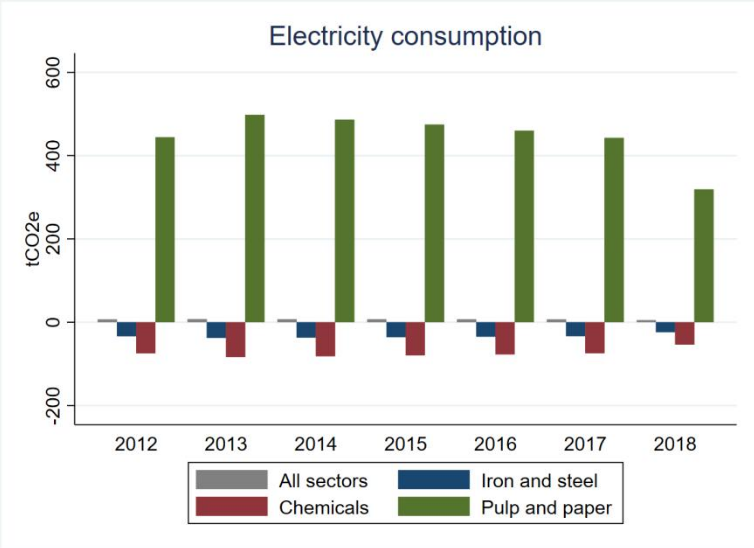
Figure 3 - effect of levy on electricity and fossil fuel consumption



Source: authors' compilation.

Next, we focus on the changes in fossil fuel consumption, by fuel type, which are presented in Figure 4. As shown in Figure 4, the introduction of the levy mostly encouraged the consumption of fossil fuel for cogeneration, regardless of the fuel type, resulting in additional emission from said fuel.

Figure 4 - effect of levy on electricity consumption by sector



Source: authors' compilation.

Given that changes in electricity consumption are very small when converted to tCO_2 equivalent, Figure 4 plots them individually, for all three sectors. As theory predicts, the introduction of the levy triggered a reduction in electricity consumption for iron and steel and chemical sectors. However, the reduction in CO_2 emissions coming from electricity consumption is rather small, and does not offset the rebound in fossil fuel consumption we observed in the previous figure. It is interesting to note that plants from the pulp and paper sector actually increase their electricity consumption because of the levy, a fact that we explain by the relatively high level of energy independence[16] inside the plants. Thus, the rebound in electricity consumption from pulp and paper plants is likely to come from a rebound in electricity generation.

6. Discussion and Concluding remarks

6.1 Implications

In this study, we find that a 1% increase in the levy results in a decrease in energy consumption, estimated around 3,755 tCO_2 equivalent on average. In addition, a 1% increase in the levy also raises of the share of fossil fuel used for power generation

[16] In this study, we voluntarily reduce our sample to only include plants with generation capacity. For the pulp and paper sector, plants with generation capacity are pulp plants, with a high degree of independence towards the electricity market.

inside the plant, a result that implies the existence of substitution possibility between electricity and fossil fuel, driven by electricity generation on site for chemical plants. We also find that this substitution is driven by additional purchases of coal and gas from the energy market. However, the magnitude of this increase is very small (less than 1% on average), which disproves the idea that energy security inside the plants was increased by cogeneration. Our results show that the dominating effect of the levy was a reduction in energy consumption, only slightly mitigated by substitution through cogeneration. These results, however, must be interpreted cautiously as the introduction of the levy took place in a very specific context. Indeed, the levy was introduced in 2012, in the aftermath of the Fukushima nuclear disaster, an event that resulted in structural changes in the Japanese energy market. The changes include a conjunction of very high electricity prices, a higher level of intermittent, renewable sources in the electricity grid, as well as relatively low fossil fuel prices. Although we are controlling for energy prices (diesel and electricity) as well as economic factors inside firms, it is possible that the conjunction of all these factors may have driven plants to substitute electricity with fossil fuel to an extent. Under these considerations, our estimated coefficient should be interpreted as an upper bound for the impact of an electricity tax on the share of fossil fuel to power CHP.

Nevertheless, our results show that substitution through cogeneration can happen, and leads to additional consumption of fossil fuel, which in turns results in CO_2 emissions. Given that the Japanese electricity mix is becoming increasingly based on renewable energy, buying additional fossil fuel from the market to power CHP leads to more emissions than if the plant had purchased electricity instead. Substitution through cogeneration thus undermines efforts towards decarbonization. Therefore, policymakers must strive not create conditions in which substitution becomes desirable. Our results show that incomplete taxation of selected energy inputs (in this case, only electricity) should be avoided, in line with Ordonez and Souza (2022).[17]

The introduction of carbon pricing is likely to result in a further decrease in energy consumption inside the plants. To avoid adverse economic effects on the production of the plants, the revenue from carbon pricing could be recycled into subsidies for decarbonization technology for the most vulnerable plants. For instance, subsidies to help plants switch their coal-powered CHP generators to gas ones, coupled with Carbon Capture and Storage (CCS) technology, or renewable energy installation coupled with batteries.

6.2 Concluding remarks

New taxation on energy products are often not well-received by the EI industry, as these sectors are the most vulnerable to an increase in energy prices. In this study, we analyze

[17] To be sure, carbon taxation has been introduced in Japan in 2012 as well, but the tax remains very low (JPY289/ tCO_2). This tax seemingly failed to prevent the rebound in fossil fuel consumption after 2012, as the rise in electricity prices was larger.

the effect of an electricity tax on energy consumption in Japanese EI plants. Specifically, we explore whether plants responded to the surge in electricity price by substituting electricity purchased from the grid with electricity generated on site, powered by fossil fuel. Using plant data from 2005 to 2018 for iron and steel, chemical and pulp and paper, we decompose energy consumption into several components, focusing on electricity generated on site and fossil fuel used to power CHP generators. Our results confirm that the tax resulted in a decrease in overall energy consumption, which is partially mitigated by an increase in fossil fuel (coal and gas) to power CHP and produce electricity on site.

Our study has several limitations. Due to data limitations, we had to restrict the sample to only include plants owned by listed firms. In addition, we have also selected plants with generation capacity, so we do not model how the policy could have influenced plants' decision to install power generation equipment. Therefore, our study does not focus on upfront installation costs and potential subsidies[18] but only examines the impact of fuel costs on energy consumption and substitution. Due to data limitations, we cannot model the changes in efficiency of CHP generators due to technological improvements or increase in fuel efficiency[19]. Finally, since we do not have access to data on production inside plants, we cannot decisively conclude whether the fall in energy consumption is due to a cut in production or gains in energy efficiency.

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[18] There are many subsidy schemes to encourage CHP installation in Japan, offered by the Ministry of Economy, Trade and Industry (METI), the Ministry of Environment, the Ministry of Land, Infrastructure, Transport and Tourism and by the Ministry of Internal Affairs and Communications.

[19] For instance, pulp plants can increase the calorific value of the produced black liquor by reducing the quality of produced fibers, and could generate more electricity with the same amount of fuel. In this study, we are using generic calorific values provided by METI and hence, cannot model these changes.

8. Authors' contribution

Aline Mortha: conceptualization, methodology, software, data curation, investigation, writing - original draft, visualization, funding acquisition, editing; **Toshi H. Arimura**: supervision, funding and data acquisition, writing-review, and editing.

9. References

Advanced Cogeneration and Energy Utilization Center JAPAN (ACEJ). (2023). Industrial installation by sector. [Sangyou-you Gyoushubetu Dounyuu Joukyou, 産業用 業種別導入状況]. [Online]. Available: https://www.ace.or.jp/web/works/works_0040.html

Agency for Natural Resources and Energy. (2020). Approved facilities and electricity consumption inside approved facilities [Nintei Jigyousho ni Okeru Nintei Jigyou no Denki Shiyouryou, 認定事業所における認定事業の電気使用量]. [Online]. Available: https://www.enecho.meti.go.jp/category/saving_and_new/saiene/kaitori/fit_nintei_genmei.html [in Japanese]

Agency for Natural Resources and Energy. (2023). Survey on price of petroleum products - survey results Sekiyu seihin kakaku chousa - chousa no kekka, 石油製品価格調査 - 調査の結果]. [Online]. Available: https://www.enecho.meti.go.jp/statistics/petroleum_and_lpgas/pl007/results.html

Bardazzi, R., Oropallo, F., & Pazienza, M. G. (2015). Do manufacturing firms react to energy prices? Evidence from Italy. *Energy Economics, 49*, 168–181. https://doi.org/10.1016/j.eneco.2015.01.014

Brucal, A., & Dechezleprêtre, A. (2021, March). *Assessing the Impact of Energy Prices on Plant-Level Environmental and Economic Performance: Evidence from Indonesian Manufacturers*. (OECD Environment Working Papers No. 170). https://doi.org/10.1787/19970900

Colmer, J., Martin, R., Muûls, M., & Wagner, U. J. (2020, November). *Does Pricing Carbon Mitigate Climate Change? Firm-Level Evidence from the European Union Emissions Trading Scheme.* (CRC TR 224 Discussion Paper No. 232). http://dx.doi.org/10.2139/ssrn.3725482

Curtis, E. M., & Lee, J. M. (2019). When do environmental regulations backfire? Onsite industrial electricity generation, energy efficiency and policy instruments. *Journal of Environmental Economics and Management, 96*, 174 – 194.

https://doi.org/10.1016/j.jeem.2019.04.004

Dismukes, D. E., & Kleit, A. N. (1999). Cogeneration and electric power industry restructuring. *Resource and Energy Economics, 21*(2), 153 – 166. https://doi.org/10.1016/S0928-7655(99)00003-2

Dong, C.G. (2012). Feed-in tariff vs. renewable portfolio standard: An empirical test of their relative effectiveness in promoting wind capacity development. *Energy Policy, 42*, 476–485. https://doi.org/10.1016/j.enpol.2011.12.014

Dussaux, D. (2020, January). *The joint effects of energy prices and carbon taxes on environmental and economic performance: Evidence from the French manufacturing sector.* (OECD Environment Working Papers No. 154). https://dx.doi.org/10.1787/b84b1b7d-en

Fan, Z., & Friedmann, S. J. (2021). Low-carbon production of iron and steel: Technology options, economic assessment, and policy. *Joule, 5*(4), 829–862. https://doi.org/10.1016/j.joule.2021.02.018

Federation of Electric Power Companies of Japan. (2020). Statistical information of electric power. Retrieved from http://www.fepc.or.jp/library/data/tokei/index.html

Flues, F., & Lutz, B. J. (2015). *The Effect of Electricity Taxation on the German Manufacturing Sector: A Regression Discontinuity Approach*. (ZEW Discussion Papers, No. 15-013). https://nbn-resolving.de/urn:nbn:de:bsz:180-madoc-387815

García-Olivares. (2015). Substitutability of electricity and renewable materials for fossil fuels in a post-carbon economy. *Energies (Basel), 8*(12), 13308 – 13343. https://doi.org/10.3390/en81212371

Gerster, A., & Lamp, S. (2020, June). *Energy Tax Exemptions and Industrial Production*. Available at SSRN: https://ssrn.com/abstract=3841576

Hattori, T. (2008, May). *An Econometric Analysis of Self-Generation for Consumption of Large Industrial Customers.* (CRIEPI Research Paper Y0727). https://www.denken.or.jp/hokokusho/pb/reportDetail?reportNoUkCode=Y07027 [in Japanese]

Hester, E. D. & Gross, A. C. (2001). Micropower. *Business Economics (Cleveland, Ohio), 36*(3), 70–76. https://www.jstor.org/stable/23488167

Ida, T., & Kinoshita, S. (2007). Analysis of demand substitution between electric power system and home power generation. Journal of public utility economics 59 (2), 43-53. [in Japanese]

Japan Electric Power eXchange (JEPX). (2023). Spot Market - transaction information [Supotto Shijou - Torihiki Jouhou, スポット市場— 取引情報]. [Online]. Available: http://www.jepx.org/market/

Jenner, S., Groba, F., & Indvik, J. (2013). Assessing the strength and effectiveness of renewable electricity feed-in tariffs in European Union countries. *Energy Policy, 52*, 385–401. https://doi.org/10.1016/j.enpol.2012.09.046

Joskow, P. (1984). The Effects of Fuel and Electricity Prices on Cogeneration in the Pulp and Paper Industry. *Energy Systems and Policy, 8*(1), 1–1.

Kabe, S. (2019, April). *Analysis of Substitutability between Electricity Purchased and Electricity Generated Onsite for Industrial Power Demand.* (CRIEPI Research Paper Y18509). https://criepi.denken.or.jp/jp/serc/source/Y18509.html [in Japanese]

Kilinc-Ata, N. (2016). The evaluation of renewable energy policies across EU countries and US states: An econometric approach. *Energy for Sustainable Development, 31*, 83–90. https://doi.org/10.1016/j.esd.2015.12.006

Kitamura, T., & Managi, S. (2016, January). *Substitution between Purchased Electricity and Fuel for Onsite Power Generation in the Manufacturing Industry: Plant level analysis in Japan.* (RIETI Discussion Paper Series 16-E-007) https://www.rieti.go.jp/en/publications/summary/16010012.html

Lehr. J. (2022, March). *The response of markups and productivity to energy tax exemptions*. Available at SSRN: https://ssrn.com/abstract=4062624

Leroutier, M. (2022). Carbon pricing and power sector decarbonization: Evidence from the UK. *Journal of Environmental Economics and Management, 111*, 102580 - . https://doi.org/10.1016/j.jeem.2021.102580

Li, J., & Lin, B. (2016). Inter-factor/inter-fuel substitution, carbon intensity, and energy-related CO_2 reduction: Empirical evidence from China. *Energy Economics, 56*, 483-494. https://doi.org/10.1016/j.eneco.2016.04.001

Marin, G., & Vona, F. (2021). The impact of energy prices on socioeconomic and environmental performance: Evidence from French manufacturing establishments, 1997 - 2015. *European Economic Review, 135*, 103739 - . https://doi.org/10.1016/j.euroecorev.2021.103739

Martin, R., de Preux, L. B., & Wagner, U. J. (2014). The impact of a carbon tax on manufacturing: Evidence from microdata. *Journal of Public Economics, 117*, 1－14. https://doi.org/10.1016/j.jpubeco.2014.04.016

Martin, R., Muûls, M., & Wagner, U. J. (2016). The Impact of the European Union Emissions Trading Scheme on Regulated Firms: What Is the Evidence after Ten Years? *Review of Environmental Economics and Policy, 10*(1), 129－148. https://doi.org/10.1093/reep/rev016

Ministry of Trade, Economy and Industry (METI). (2020). Pollutant release and transfer register (PRTR) [Online]. Available: https://www.meti.go.jp/policy/chemical_management/law/prtr/6.html [in Japanese]

Moller, N. F.. (2017). Energy demand, substitution and environmental taxation: An econometric analysis of eight subsectors of the Danish economy. *Energy Economics, 61*, 97－109. https://doi.org/10.1016/j.eneco.2016.10.004

Morley, B. (2012). Empirical evidence on the effectiveness of environmental taxes. *Applied Economics Letters, 19*(18), 1817–1820. https://doi.org/10.1080/13504851.2011.650324

Mortha, A., Yajima, N., & Arimura, T.H. (2022, March). *Impact of the Feed-in-Tariff Exemption on Energy Consumption in Japanese Industrial Plants*. (TCER Working Paper E-169). https://www.tcer.or.jp/wp/pdf/e169.pdf

Ordonez, P.J., & Souza, M. (2022, May). *Fuel Switching Under Incomplete Carbon Pricing*. Available at https://ideas.repec.org/p/ags/aaea22/322321.html

Petrick, S., & Wagner, U.J. (2014, March). *The Impact of Carbon Trading on Industry: Evidence from German Manufacturing Firms*. Available at https://econpapers.repec.org/paper/zbwifwkwp/1912.htm

Rahnama Mobarakeh, M., Santos Silva, M., & Kienberger, T. (2021). Pulp and Paper Industry: Decarbonisation Technology Assessment to Reach CO_2 Neutral Emissions—An Austrian Case Study. *Energies (Basel), 14*(4), 1161–. https://doi.org/10.3390/en14041161

Saitama Prefecture. (2021). Publications on the status of plans and implementation [Keikaku, Jisshi Joukyou no Kouhyou, 計画· 実施状況の公表] [Online]. Available: https://www.pref.saitama.lg.jp/a0502/keikakukouhyou.html [in Japanese]

Santos Silva, J. M. C., & Tenreyro, S. (2006). The Log of Gravity. *The Review of Economics and Statistics, 88*(4), 641–658. https://doi.org/10.1162/rest.88.4.641

Schiffer, Z. J., & Manthiram, K. (2017). Electrification and Decarbonization of the Chemical Industry. *Joule, 1*(1), 10–14. https://doi.org/10.1016/j.joule.2017.07.008

Serletis, A., Timilsina, G. R., & Vasetsky, O. (2010). Interfuel substitution in the United States. *Energy Economics, 32*(3), 737–745. https://doi.org/10.1016/j.eneco.2010.01.013

Taghizadeh-Hesary, F., Mortha, A., Farabi-Asl, H., Sarker, T., Chapman, A., Shigetomi, Y., & Fraser, T. (2020). Role of energy finance in geothermal power development in Japan. *International Review of Economics & Finance, 70*, 398–412. https://doi.org/10.1016/j.iref.2020.06.011

Tokyo Metropolitan Government. (2021). Public information [Koukai Jouhou, 公開情報]. Compiled by the Bureau of Environment [Online]. Available: https://www9.kankyo.metro.tokyo.lg.jp/koukai/koukai.html [in Japanese]

Toyo Keizai. (2020). Company quarterly publications [Kaisha Shikihou, 会社四季報] [Online]. Available: https://biz.toyokeizai.net/data/publications/#publication316 [in Japanese]

von Graevenitz, K., & Rottner, E. (2022, October). *Do manufacturing plants respond to exogenous changes in electricity prices? Evidence from administrative micro-data.* (ZEW Discussion Paper No. 22-038, Mannheim). https://www.zew.de/publikationen/do-manufacturing-plants-respond-to-exogenous-changes-in-electricity-prices-evidence-from-administrative-micro-data

Wooldridge, J. M. (2010). *Econometric analysis of cross section and panel data, Second Edition*. (2nd edition). The MIT Press.

Yamazaki, A. (2017). Jobs and climate policy: Evidence from British Columbia's revenue-neutral carbon tax. *Journal of Environmental Economics and Management, 83*, 197–216. https://doi.org/10.1016/j.jeem.2017.03.003

10. Appendix

Appendix A. Full estimation results - substitution indicators

A1. Vertical integration, electricity

Variable: Vertical integration (electricity)	All PPML	Iron and Steel PPML	Chemicals PPML	Pulp and Paper PPML
Electricity spot market price	0.0175* (0.00963)	0.00175 (0.0134)	0.0276* (0.0145)	0.00121 (0.00551)
Industrial diesel price	-0.00281* (0.00149)	-0.00657 (0.00544)	-0.00201 (0.00215)	-0.00267* (0.00152)
FIT levy	0.0166 (0.0549)	-0.0599 (0.0875)	0.0620 (0.0767)	-0.0883 (0.0575)
Number of employees inside plant	0.0000471 (0.000113)	0.000201 (0.000493)	0.0000504 (0.000148)	-0.000169 (0.000199)
Saitama ETS	-0.193** (0.0774)	no observations	no observations	-0.0772 (0.0718)
Tokyo ETS	-0.0585 (0.120)	0.124 (0.149)	no observations	no observations
Return on Equity (firm-level)	-0.0119*** (0.00289)	-0.0103*** (0.00347)	0.00952 (0.298)	0.0215 (0.746)
Annual sales (firm-level, ln)	-0.0853 (0.248)	0.0687 (0.273)	-0.269 (0.386)	0.502** (0.256)
February	-0.0299 (0.0260)	-0.00388 (0.0143)	-0.0540 (0.0422)	0.00961 (0.00802)
March	-0.00323 (0.0215)	0.00173 (0.0212)	-0.0112 (0.0352)	0.0115 (0.0155)
April	-0.0307 (0.0355)	0.0424 (0.0377)	-0.0408 (0.0532)	-0.0411 (0.0384)
May	-0.0326 (0.0416)	0.0169 (0.0503)	-0.0282 (0.0594)	-0.0640 (0.0606)
June	-0.0239 (0.0369)	-0.00869 (0.0558)	-0.0198 (0.0566)	-0.0336 (0.0247)
July	0.0117 (0.0538)	0.0664 (0.0647)	0.00463 (0.0851)	0.00706 (0.0390)
August	-0.0185 (0.0406)	0.0575 (0.0689)	-0.0378 (0.0607)	-0.00475 (0.0408)
September	-0.0114 (0.0387)	0.0512 (0.0664)	-0.0190 (0.0586)	-0.0149 (0.0342)
October	-0.0261 (0.0316)	0.0169 (0.0504)	-0.0231 (0.0484)	-0.0461* (0.0272)
November	-0.0365 (0.0279)	-0.0292 (0.0364)	-0.0461 (0.0419)	-0.00869 (0.0237)
December	-0.0211 (0.0271)	-0.0268 (0.0349)	-0.0342 (0.0414)	0.0201 (0.0134)
Number of plants	91	32	42	17

Number of observations	8,894	2,380	4,821	1,693

Source: authors' compilation. Estimation method: Poisson Pseudo Maximum Likelihood (PPML). Standard errors in parenthesis, clustered by plant. "*", "**" and "***" represent significance at 10%, 5% and 1%, respectively.

A2. Vertical integration, fossil fuel

Variable: vertical integration (fossil fuel)	All PPML	Iron and Steel PPML	Chemicals PPML	Pulp and Paper PPML
Electricity spot market price	0.00754	-0.00404	0.0116	0.00215
	(0.00473)	(0.00977)	(0.00720)	(0.00188)
Industrial diesel price	-0.000952*	-0.00247	-0.000904	-0.000570**
	(0.000545)	(0.00426)	(0.000662)	(0.000268)
FIT levy	0.0431**	-0.0114	0.0716***	-0.00184
	(0.0180)	(0.0482)	(0.0267)	(0.0136)
Number of employees inside plant	0.000130**	-0.0000648	0.000117*	0.0000296
	(0.0000643)	(0.000343)	(0.0000673)	(0.0000679)
Saitama ETS	-0.119***	no observations	no observations	-0.0611***
	(0.0326)			(0.0165)
Tokyo ETS	-0.0607	0.0590	no observations	no observations
	(0.0389)	(0.0847)		
Return on Equity (firm-level)	-0.00598***	-0.00543***	-0.104	0.0730
	(0.000391)	(0.00121)	(0.121)	(0.0879)
Annual sales (firm-level, ln)	-0.0759	0.0867	-0.126	-0.0135
	(0.0737)	(0.131)	(0.112)	(0.0500)
February	-0.00429	-0.0247	-0.00268	-0.000692
	(0.00559)	(0.0308)	(0.00674)	(0.00323)
March	0.00220	-0.0216	0.00441	0.00667
	(0.00578)	(0.0205)	(0.00860)	(0.00438)
April	-0.00171	-0.0101	-0.00406	0.00585
	(0.00612)	(0.0418)	(0.00750)	(0.00443)
May	0.00595	0.0229	0.00435	0.00173
	(0.00838)	(0.0559)	(0.00917)	(0.0100)
June	0.0147*	0.0148	0.0157	0.0126**
	(0.00829)	(0.0547)	(0.00965)	(0.00624)
July	0.0343***	0.0506	0.0371**	0.0211**
	(0.0125)	(0.0586)	(0.0175)	(0.00942)
August	0.0147	0.0417	0.0101	0.0150**
	(0.00925)	(0.0558)	(0.0117)	(0.00715)
September	0.0127	0.0270	0.00880	0.0161**
	(0.0114)	(0.0626)	(0.0148)	(0.00668)
October	0.0189*	0.0158	0.0244*	0.00900*

	(0.0102)	(0.0525)	(0.0143)	(0.00481)
November	0.0144	-0.0323	0.0261*	0.00769**
	(0.00899)	(0.0285)	(0.0141)	(0.00390)
December	0.00369	-0.0498	0.0132*	0.00448*
	(0.00534)	(0.0317)	(0.00690)	(0.00257)
Number of plants	95	31	44	20
Number of observations	8,716	1,971	4,887	1,858

Source: authors' compilation. Estimation method: Poisson Pseudo Maximum Likelihood (PPML). Standard errors in parenthesis, clustered by plant. "*", "**" and "***" represent significance at 10%, 5% and 1%, respectively.

A3. Vertical integration, fossil fuel type

Variable: vertical integration (fossil fuel, by fuel type	Byproducts and waste PPML	Coal PPML	Oil PPML	Gas PPML
Electricity spot market price	-0.00628	-0.00673	-0.000611	0.000547
	(0.00737)	(0.0101)	(0.0179)	(0.0133)
Industrial diesel price	0.000756	0.00334**	-0.00661*	0.00102
	(0.00200)	(0.00167)	(0.00378)	(0.00153)
FIT levy	0.00275	0.290*	-0.526***	0.0994*
	(0.0793)	(0.160)	(0.142)	(0.0521)
Number of employees inside plant	0.000220	-0.000219	0.000305	-0.000299
	(0.000140)	(0.000270)	(0.000185)	(0.000196)
Saitama ETS	-0.123	no observations	-4.591***	0.0599
	(0.0971)		(1.423)	(0.0857)
Tokyo ETS	no observations	no observations	1.589***	-0.220*
			(0.181)	(0.125)
Return on Equity (firm-level)	-0.0340***	0.176	2.016***	-0.00421***
	(0.0126)	(0.325)	(0.656)	(0.000873)
Annual sales (firm-level, ln)	0.521	-0.703**	-0.419	-0.126
	(0.447)	(0.331)	(0.559)	(0.254)
February	-0.00593	-0.0106	0.0211	0.00298
	(0.0111)	(0.0234)	(0.0191)	(0.0125)
March	-0.00957	0.00360	-0.000523	0.00402
	(0.0289)	(0.0170)	(0.0387)	(0.0161)
April	-0.0201	-0.133**	0.0901*	-0.0192
	(0.0309)	(0.0669)	(0.0545)	(0.0305)
May	-0.0104	-0.164***	0.125*	-0.0395
	(0.0525)	(0.0546)	(0.0671)	(0.0297)
June	0.0142	-0.127***	0.0959	-0.0334
	(0.0365)	(0.0483)	(0.0634)	(0.0256)

July	0.0417	-0.116**	0.102	-0.0290
	(0.0640)	(0.0473)	(0.0737)	(0.0258)
August	0.0268	-0.0758**	0.0839	-0.0222
	(0.0311)	(0.0373)	(0.0521)	(0.0240)
September	0.0545**	-0.0788	0.0973*	-0.0187
	(0.0278)	(0.0480)	(0.0578)	(0.0295)
October	0.0296	-0.0573	0.0541	-0.0142
	(0.0245)	(0.0409)	(0.0567)	(0.0223)
November	0.0104	-0.0497	0.0261	0.0104
	(0.0293)	(0.0340)	(0.0416)	(0.0197)
December	-0.00664	-0.0699**	0.0189	-0.00930
	(0.0175)	(0.0288)	(0.0334)	(0.0114)
Number of plants	33	21	62	61
Number of observations	3,209	1,992	5,727	5,881

Source: authors' compilation. Estimation method: Poisson Pseudo Maximum Likelihood (PPML). Standard errors in parenthesis, clustered by plant. "*", "**" and "***" represent significance at 10%, 5% and 1%, respectively.

Appendix B. Full estimation results - energy consumption indicators

B1. Electricity generation

Electricity generation	All PPML	All NB2	Iron and Steel PPML	Iron and Steel NB2	Chemical PPML	Chemical NB2	Pulp and Paper PPML	Pulp and Paper NB2
Electricity spot market price	0.00309	-0.0313	0.00379	-0.0326	0.00740	-0.0393	0.00613	-0.0621
	(0.00975)	(0.0215)	(0.00537)	(0.0359)	(0.0168)	(0.0278)	(0.00463)	(0.0501)
Industrial diesel price	-0.000583	0.000557	0.00164	0.00383	-0.00110	-0.000446	-0.00275	-0.0000599
	(0.00153)	(0.00394)	(0.00183)	(0.00784)	(0.00220)	(0.00559)	(0.00211)	(0.00519)
FIT levy	0.0245	-0.00500	0.0172	0.193	0.0472	-0.0737	-0.0665	-0.175
	(0.0651)	(0.101)	(0.0590)	(0.214)	(0.0809)	(0.111)	(0.0484)	(0.277)
Number of employees inside plant	0.0000317	0.000203	-0.000365	0.000275	0.000135	-0.000288	-0.000272	0.000338
	(0.000101)	(0.000334)	(0.000292)	(0.000671)	(0.000112)	(0.000564)	(0.000237)	(0.00323)
Saitama ETS	-0.311***	1.213***	no obs.	no obs.	no obs.	no obs.	-0.240***	1.503**
	(0.0791)	(0.280)					(0.0664)	(0.583)
Tokyo ETS	-0.115	0.833***	-0.126	0.442	no obs.	no obs.	no obs.	no obs.
	(0.158)	(0.299)	(0.112)	(0.557)				
Return on Equity	-0.0120***	0.000483	-0.0161***	-0.00132	0.468*	0.720	0.499	1.940
	(0.00313)	(0.745)	(0.00118)	(1.298)	(0.274)	(1.630)	(1.051)	(3.228)

(firm-level)								
Annual sales (firm-level, ln)	0.0418 (0.351)	0.0708 (0.123)	0.111 (0.211)	-0.0757 (0.279)	-0.174 (0.525)	0.226 (0.207)	0.357 (0.359)	-0.155 (0.571)
February	-0.121*** (0.0276)	-0.0944** (0.0469)	-0.121*** (0.0337)	-0.127*** (0.0367)	-0.136*** (0.0412)	-0.145* (0.0846)	-0.0651* (0.0386)	0.00809 (0.0372)
March	-0.0333 (0.0392)	-0.0860 (0.0569)	-0.0344 (0.0249)	-0.214** (0.0911)	-0.0530 (0.0571)	-0.120 (0.0878)	0.0675*** (0.0135)	0.0106 (0.0471)
April	-0.0796 (0.0851)	-0.0610 (0.0528)	-0.0758*** (0.0249)	-0.190** (0.0938)	-0.102 (0.130)	-0.0852 (0.0751)	0.0286 (0.0451)	0.0313 (0.0646)
May	-0.0508 (0.0659)	-0.0337 (0.0527)	-0.105 (0.0813)	-0.108 (0.116)	-0.0460 (0.0930)	-0.0438 (0.0701)	0.0251 (0.0890)	-0.0413 (0.0943)
June	0.000984 (0.0618)	0.00576 (0.0565)	-0.102 (0.0708)	-0.144 (0.116)	0.0220 (0.0866)	0.0129 (0.0796)	0.0710 (0.0556)	0.0754 (0.0950)
July	0.0702 (0.0763)	0.0663 (0.0605)	0.0532 (0.0388)	-0.0423 (0.103)	0.0699 (0.112)	0.0961 (0.0856)	0.106*** (0.0309)	0.0902 (0.0943)
August	0.0626 (0.0587)	0.0760 (0.0540)	0.0534 (0.0327)	-0.0112 (0.0842)	0.0632 (0.0858)	0.112 (0.0843)	0.0664 (0.0469)	0.0833 (0.120)
September	-0.0197 (0.0507)	-0.00209 (0.0619)	0.0289 (0.0377)	-0.0739 (0.109)	-0.0546 (0.0705)	-0.0141 (0.0989)	0.0785** (0.0372)	0.0458 (0.103)
October	-0.0226 (0.0408)	-0.0632 (0.0658)	0.0222 (0.0375)	-0.245 (0.153)	-0.0563 (0.0552)	-0.0228 (0.117)	0.0703* (0.0359)	-0.0665 (0.0566)
November	-0.0713 (0.0507)	-0.103* (0.0575)	-0.0687 (0.0634)	-0.397** (0.177)	-0.106 (0.0673)	-0.0145 (0.0730)	0.0752** (0.0363)	-0.0321 (0.0612)
December	-0.00765 (0.0405)	-0.0598 (0.0415)	-0.0206 (0.0379)	-0.293** (0.138)	-0.0243 (0.0538)	0.00505 (0.0484)	0.0795** (0.0392)	0.00746 (0.0714)
Constant	/	-1.796 (1.470)	/	-0.0898 (3.340)	/	-3.353 (2.849)	/	1.190 (7.156)
Number of plants	91		32		42		17	
Number of observations	8,907		2,387		4,827		1,693	

Source: authors' compilation. Standard errors in parenthesis, clustered by plant for PPML. Bootstrap standard errors are used for NB2. "*", "**" and "***" represent significance at 10%, 5% and 1%, respectively.

B2. Fossil fuel for cogeneration

Variable: fossil fuel for cogeneration	All PPML	All NB2	Iron and Steel PPML	Iron and Steel NB2	Chemical PPML	Chemical NB2	Pulp and Paper PPML	Pulp and Paper NB2
Electricity spot market	-0.00817**	-0.00358	-0.00845	-0.00617	-0.00290	-0.00171	-0.00401	0.00405

price	(0.00415)	(0.00481)	(0.00975)	(0.0153)	(0.00286)	(0.00652)	(0.00730)	(0.00570)
Industrial	-0.00112	-0.000965	-0.00324	-0.00404*	-0.000416	-0.00103	-0.00102	-0.000407
diesel price	(0.000695)	(0.000918)	(0.00279)	(0.00216)	(0.000772)	(0.000960)	(0.00113)	(0.00141)
FIT levy	-0.0549*	-0.0499*	-0.249***	-0.126	-0.0128	-0.0336	-0.144**	-0.0788
	(0.0320)	(0.0256)	(0.0631)	(0.131)	(0.0274)	(0.0321)	(0.0673)	(0.0483)
Number of employees	-0.0000762	0.000251***	-0.000187	0.000379	0.0000764	0.000131	0.000332	0.000224
inside plant	(0.000131)	(0.0000867)	(0.000353)	(0.000311)	(0.0000474)	(0.000155)	(0.000272)	(0.000517)
Saitama ETS	-0.169***	0.0166	no obs.	no obs.	no obs.	no obs.	-0.137**	-0.126
	(0.0400)	(0.100)					(0.0674)	(0.0812)
Tokyo ETS	0.0679	-0.365*	0.356**	0.0300	no obs.	no obs.	no obs.	no obs.
	(0.0668)	(0.189)	(0.156)	(0.304)				
Return on Equity	-0.0199***	-0.0147	-0.0206***	-0.0103	0.0721	-0.331	-0.641	0.248
(firm-level)	(0.00285)	(0.188)	(0.000633)	(0.781)	(0.115)	(0.280)	(0.532)	(0.340)
Annual sales	0.288	0.294*	0.702	0.303	-0.0553	0.417**	1.073**	0.304
(firm-level, ln)	(0.176)	(0.151)	(0.467)	(0.269)	(0.115)	(0.173)	(0.433)	(0.329)
February	-0.0999***	-0.0960***	-0.126***	-0.0702***	-0.104***	-0.137***	-0.0556***	-0.0138
	(0.0117)	(0.0259)	(0.00963)	(0.0203)	(0.0178)	(0.0439)	(0.0192)	(0.0211)
March	-0.0530***	-0.0612***	-0.0647***	-0.0208	-0.0621**	-0.0939***	0.00955	0.0352***
	(0.0174)	(0.0209)	(0.0174)	(0.0474)	(0.0253)	(0.0336)	(0.00947)	(0.0133)
April	-0.0848***	-0.107***	-0.0400	-0.139***	-0.0965***	-0.110***	-0.0588***	-0.00728
	(0.0199)	(0.0226)	(0.0247)	(0.0493)	(0.0329)	(0.0316)	(0.0178)	(0.0210)
May	-0.0853***	-0.128***	-0.0553	-0.202***	-0.0805***	-0.0885***	-0.0944*	-0.0982*
	(0.0195)	(0.0242)	(0.0379)	(0.0749)	(0.0305)	(0.0220)	(0.0520)	(0.0589)
June	-0.0887***	-0.109***	-0.0744*	-0.0763	-0.0890***	-0.103***	-0.0554	-0.0464*
	(0.0146)	(0.0263)	(0.0413)	(0.0901)	(0.0176)	(0.0288)	(0.0431)	(0.0239)
July	-0.0483	-0.0826***	0.0363	-0.0250	-0.0442	-0.0564*	-0.161*	-0.0868*
	(0.0367)	(0.0310)	(0.0471)	(0.105)	(0.0440)	(0.0339)	(0.0923)	(0.0465)
August	-0.00288	-0.0958***	0.0439	-0.108	-0.00291	-0.0532*	-0.0440	-0.113***
	(0.0161)	(0.0325)	(0.0441)	(0.105)	(0.0167)	(0.0305)	(0.0424)	(0.0402)
September	-0.0755***	-0.115***	0.0347	-0.0461	-0.114***	-0.135***	-0.0479	-0.0293

	(0.0287)	(0.0326)	(0.0431)	(0.107)	(0.0377)	(0.0322)	(0.0442)	(0.0221)
October	-0.0537**	-0.0747***	0.00805	-0.0197	-0.0705**	-0.0816***	-0.0335	-0.0168
	(0.0240)	(0.0242)	(0.0405)	(0.0844)	(0.0333)	(0.0275)	(0.0281)	(0.0174)
November	-0.0793***	-0.0842**	-0.0409	-0.0288	-0.0935***	-0.0946*	-0.0362	-0.00123
	(0.0157)	(0.0337)	(0.0335)	(0.0562)	(0.0207)	(0.0533)	(0.0280)	(0.0200)
December	-0.00882	-0.0114	-0.000222	0.00316	-0.00290	0.00665	-0.00937	-0.0110
	(0.00936)	(0.00919)	(0.0266)	(0.0395)	(0.0107)	(0.0132)	(0.0126)	(0.0179)
Constant	/	-1.958	/	-2.590	/	-3.433	/	-0.872
		(2.044)		(3.329)		(2.353)		(4.327)
Number of plants	95		31		44		20	
Number of observations	8,717		1,972		4,887		1,858	

Source: authors' compilation. Standard errors in parenthesis, clustered by plant for PPML. Bootstrap standard errors are used for NB2. "*", "**" and "***" represent significance at 10%, 5% and 1%, respectively.

B3. Fossil fuel for cogeneration and boilers, by fuel type

Variable: fossil fuel consumption for cogeneration and boilers	Byproducts and waste PPML	Byproducts and waste NB2	Coal PPML	Coal NB2	Oil PPML	Gas PPML	Gas NB2
Electricity spot market price	-0.00418	-0.0240	0.000627	-0.0203	-0.0139	-0.000349	0.00356
	(0.00623)	(0.0276)	(0.00387)	(0.0128)	(0.0140)	(0.0182)	(0.0228)
Industrial diesel price	-0.000474	0.00177	0.000537	0.00280	-0.00595***	0.00135	0.00102
	(0.00116)	(0.00411)	(0.000666)	(0.00261)	(0.00206)	(0.00185)	(0.00359)
FIT levy	-0.133***	-0.351***	0.0322	-0.0226	-0.306**	-0.0120	0.152
	(0.0462)	(0.115)	(0.0379)	(0.0430)	(0.143)	(0.120)	(0.109)
Number of employees inside plant	0.000151	0.00102***	-0.0000586	-0.000279	-0.000264	0.0000469	0.0000904
	(0.000128)	(0.000286)	(0.0000922)	(0.000234)	(0.000201)	(0.000222)	(0.000426)
Saitama ETS	-0.0798	1.972***	no obs.	no obs.	-3.894***	-0.0761	0.886***
	(0.0509)	(0.611)			(1.428)	(0.194)	(0.230)
Tokyo ETS	no obs.	no obs.	no obs.	no obs.	0.494***	-0.00950	0.372
					(0.158)	(0.301)	(0.279)
Return on Equity (firm-level)	-0.0391***	-0.0297	0.216	-0.796	1.163*	-0.0168***	-0.00271
	(0.0135)	(0.907)	(0.194)	(0.551)	(0.690)	(0.00176)	(0.682)
Annual sales (firm-level, ln)	0.371	0.640*	-0.116	0.935	-0.149	0.291	0.0194
	(0.293)	(0.357)	(0.149)	(0.620)	(0.526)	(0.658)	(0.155)
February	-0.116***	-0.116***	-0.0822***	-0.0954***	-0.0589*	-0.124**	-0.0544

	(0.0194)	(0.0445)	(0.0191)	(0.0286)	(0.0334)	(0.0513)	(0.0334)
March	-0.0607	-0.0739	0.0151	-0.0831*	-0.00263	-0.0482	0.0115
	(0.0397)	(0.0476)	(0.0226)	(0.0487)	(0.0432)	(0.0308)	(0.0449)
April	-0.0383	-0.0178	-0.154**	-0.253***	-0.0292	-0.0873	-0.127***
	(0.0409)	(0.0390)	(0.0664)	(0.0909)	(0.0660)	(0.0713)	(0.0452)
May	-0.0274	-0.0566	-0.276***	-0.630***	-0.0411	-0.107	-0.0951
	(0.0392)	(0.0822)	(0.0684)	(0.156)	(0.0524)	(0.0676)	(0.0668)
June	-0.0408	-0.0822	-0.167***	-0.320***	-0.0826	-0.0955**	-0.00883
	(0.0377)	(0.0861)	(0.0415)	(0.0991)	(0.0639)	(0.0486)	(0.0907)
July	-0.0231	-0.0168	-0.0695	-0.155**	-0.128	0.0201	0.0779
	(0.0449)	(0.0721)	(0.0548)	(0.0641)	(0.145)	(0.0917)	(0.107)
August	0.0167	0.0160	-0.0125	-0.0768*	-0.0132	-0.0181	0.0525
	(0.0332)	(0.0698)	(0.0311)	(0.0460)	(0.0448)	(0.0852)	(0.0899)
September	-0.0447	-0.0299	-0.0891	-0.267***	-0.0106	-0.0543	0.0832
	(0.0408)	(0.0706)	(0.0617)	(0.0946)	(0.0471)	(0.0794)	(0.0944)
October	-0.0184	0.0132	-0.0794*	-0.342***	-0.0987	-0.0821	0.0938
	(0.0343)	(0.0835)	(0.0470)	(0.131)	(0.0618)	(0.0588)	(0.0858)
November	-0.0639*	-0.0449	-0.115***	-0.292**	-0.140***	-0.0903	0.0409
	(0.0345)	(0.0638)	(0.0367)	(0.142)	(0.0499)	(0.0706)	(0.0881)
December	-0.00988	0.0168	-0.0517**	-0.131***	-0.00524	-0.00934	0.0457
	(0.0213)	(0.0433)	(0.0201)	(0.0487)	(0.0244)	(0.0546)	(0.0555)
Constant	/	-9.737*	/	-11.71	/	/	-1.098
		(4.981)		(8.649)			(1.954)
Number of plants	33		21		62	61	
Number of observations	3,209		1,992		5,732	5,888	

Source: authors' compilation. Standard errors in parenthesis, clustered by plant for PPML. Bootstrap standard errors are used for NB2. No convergence was achieved with NB2 when using oil consumption as dependent variable. "*", "**" and "***" represent significance at 10%, 5% and 1%, respectively. "Byproduct and waste" include gas from coke oven, blast furnace and converters, hydrocarbon reported as byproducts (oil or gas), recovered black liquor and waste material. "Coal" includes coal, coal coke and petroleum coke. "Oil" includes kerosene, diesel, naphtha, heavy and crude oil (excluding NGL). "Gas" includes LPG, LNG, piped gas, NGL and condensate and natural gas.

B4. Energy consumption

Variable: Energy consumption	All PPML	All NB2	Iron and Steel PPML	Iron and Steel NB2	Chemical PPML	Chemical NB2	Pulp and Paper PPML	Pulp and Paper NB2
Electricity spot	-0.00391	-0.00437	0.00474	0.00578	-0.00739	-0.0103**	-0.00296	0.00268
market price	(0.00469)	(0.00454)	(0.00442)	(0.0106)	(0.00515)	(0.00443)	(0.00658)	(0.00501)
Industrial	0.000602	0.000694	-0.00108	-0.00250*	0.00197**	0.00152**	-0.000668	0.000140
diesel price	(0.000698)	(0.000631)	(0.00157)	(0.00151)	(0.000995)	(0.000722)	(0.000953)	(0.00127)

FIT levy	-0.0647	-0.0844**	-0.0936*	-0.105	-0.0601	-0.0812**	-0.133**	-0.0696
	(0.0529)	(0.0354)	(0.0547)	(0.0740)	(0.0681)	(0.0343)	(0.0649)	(0.0430)
Number of employees inside plant	0.0000258	0.000196**	0.000147	0.000361	-0.0000175	-0.0000485	0.000407*	0.000239
	(0.0000926)	(0.0000989)	(0.000204)	(0.000236)	(0.0000942)	(0.000125)	(0.000229)	(0.000474)
Saitama ETS	-0.0297	0.138	no obs.	no obs.	no obs.	no obs.	-0.00771	0.0106
	(0.0994)	(0.149)					(0.109)	(0.134)
Tokyo ETS	0.00648	-0.697***	0.0876	-0.504***	no obs.	no obs.	no obs.	no obs.
	(0.0593)	(0.0719)	(0.120)	(0.172)				
Return on Equity	-0.0122***	-0.00971	-0.0116***	-0.00833	0.0602	0.00625	-0.894	-0.0126
(firm-level)	(0.000606)	(0.237)	(0.000856)	(0.745)	(0.190)	(0.173)	(0.548)	(0.308)
Annual sales	0.113	0.129	0.422	0.192	-0.328	0.156	1.018***	0.358
(firm-level, ln)	(0.147)	(0.0981)	(0.278)	(0.183)	(0.228)	(0.112)	(0.288)	(0.302)
February	-0.106***	-0.0841***	-0.119***	-0.0565**	-0.0987***	-0.123***	-0.0554***	-0.0121
	(0.00708)	(0.0182)	(0.00533)	(0.0220)	(0.0124)	(0.0307)	(0.0105)	(0.0175)
March	-0.0629***	-0.0477***	-0.0510**	-0.00669	-0.0773***	-0.0841***	-0.000451	0.0319***
	(0.0154)	(0.0157)	(0.0253)	(0.0337)	(0.0214)	(0.0302)	(0.00710)	(0.0118)
April	-0.0625***	-0.0707***	-0.0355**	-0.0812***	-0.0713*	-0.0954***	-0.0636***	0.00114
	(0.0181)	(0.0219)	(0.0145)	(0.0301)	(0.0379)	(0.0275)	(0.0158)	(0.0215)
May	-0.0421***	-0.0818***	-0.0173	-0.0962***	-0.0373*	-0.0789***	-0.0891**	-0.0782
	(0.0119)	(0.0201)	(0.0211)	(0.0370)	(0.0208)	(0.0184)	(0.0436)	(0.0514)
June	-0.0718***	-0.0666***	-0.0342	-0.00914	-0.0914***	-0.0915***	-0.0642*	-0.0397*
	(0.0111)	(0.0172)	(0.0232)	(0.0366)	(0.0140)	(0.0232)	(0.0342)	(0.0224)
July	-0.0524	-0.0686**	0.0168	0.0460	-0.0964	-0.104**	-0.154**	-0.0767*
	(0.0348)	(0.0322)	(0.0301)	(0.0316)	(0.0624)	(0.0486)	(0.0745)	(0.0400)
August	-0.0299*	-0.0653***	0.0225	-0.0185	-0.0656***	-0.0817***	-0.0581	-0.104***
	(0.0162)	(0.0145)	(0.0275)	(0.0294)	(0.0219)	(0.0257)	(0.0356)	(0.0310)
September	-0.0877**	-0.0711***	0.00880	0.0525**	-0.178***	-0.142***	-0.0560	-0.0275
	(0.0353)	(0.0154)	(0.0308)	(0.0263)	(0.0523)	(0.0309)	(0.0374)	(0.0186)
October	-0.0625*	-0.0563***	0.0297	0.0475*	-0.149**	-0.116***	-0.0381	-0.00816
	(0.0361)	(0.0183)	(0.0250)	(0.0287)	(0.0584)	(0.0347)	(0.0248)	(0.0168)
November	-0.0639**	-0.0726**	-0.0147	0.00921	-0.0995**	-0.111**	-0.0470**	0.00495

	*	*			*			
	(0.0173)	(0.0252)	(0.0265)	(0.0254)	(0.0235)	(0.0433)	(0.0229)	(0.0193)
December	-0.00742	-0.0156*	0.0112	0.00672	-0.00846	-0.0121	-0.0138	-0.00781
	(0.00894)	(0.00806)	(0.0222)	(0.0203)	(0.00753)	(0.00861)	(0.00976)	(0.0168)
Constant	/	0.553	/	-0.659	/	0.387	/	-1.374
		(1.325)		(2.340)		(1.559)		(3.979)
Number of plants	99		35		44		20	
Number of observations	9,240		2,495		4,887		1,858	

Source: authors' compilation. Standard errors in parenthesis, clustered by plant for PPML. Bootstrap standard errors are used for NB2. "*", "**" and "***" represent significance at 10%, 5% and 1%, respectively.

Appendix C. Methodology used for conversion of electricity into CO_2 emissions

In Step 1, we computed a weighted average for all electricity variables, based on the number of observations per region, for each year. Regions are defined by the jurisdiction of each of the ten monopolistic electricity companies in Japan. The weights are given in the table below:

C1. Yearly weights per region

Panel A - iron and steel

	Hokkaido	Tohoku	Tokyo	Chubu	Hokuriku	Kansai	Chugoku	Shikoku	Kyushu
2012	4%	8%	32%	16%	5%	15%	9%	2%	9%
2013	2%	7%	33%	15%	6%	16%	11%	2%	7%
2014	2%	6%	31%	16%	7%	16%	11%	2%	7%
2015	3%	7%	30%	15%	7%	16%	11%	2%	8%
2016	3%	7%	30%	16%	7%	15%	13%	3%	7%
2017	3%	4%	32%	15%	8%	17%	11%	3%	7%
2018	3%	5%	32%	16%	9%	17%	9%	2%	7%
Total	3%	8%	31%	15%	6%	16%	10%	2%	9%

Panel B - chemicals

	Hokkaido	Tohoku	Tokyo	Chubu	Hokuriku	Kansai	Chugoku	Shikoku	Kyushu
2012	2%	6%	42%	11%	4%	3%	17%	6%	8%
2013	3%	7%	40%	12%	4%	3%	18%	5%	8%
2014	3%	7%	40%	9%	4%	3%	18%	7%	8%
2015	2%	7%	43%	8%	3%	6%	17%	6%	8%
2016	2%	7%	43%	11%	4%	9%	17%	4%	4%
2017	2%	7%	39%	8%	3%	12%	21%	3%	5%
2018	2%	9%	39%	11%	2%	11%	20%	4%	4%
Total	2%	7%	39%	12%	5%	5%	18%	6%	6%

Panel C - pulp and paper

	Hokkaido	Tohoku	Tokyo	Chubu	Hokuriku	Kansai	Chugoku	Shikoku	Kyushu
2012	5%	16%	21%	26%	0%	5%	16%	11%	0%
2013	5%	16%	16%	32%	0%	5%	11%	16%	0%
2014	6%	17%	17%	28%	0%	5%	11%	17%	0%
2015	6%	17%	17%	28%	0%	0%	8%	25%	0%
2016	5%	16%	16%	26%	0%	0%	5%	32%	0%
2017	6%	11%	17%	28%	0%	0%	6%	33%	0%
2018	6%	12%	18%	24%	0%	0%	6%	35%	0%
Total	9%	16%	13%	31%	2%	5%	10%	14%	0%

Source: authors' compilation. Weights refer to the percentage of observations for each region, inside the analyzed sample.

Then, in Step 2, we computed the emission factor, that is, for each kWh, the amount of CO_2 that is emitted. Emission factors are published every year by the Ministry of Environment[i]. If green menus (i.e., renewable electricity) are offered, we use the emission factor for the overall company. Since each of the ten electricity companies reported a different emission factor each year, we computed a weighted average of the emission factor, for each year, based on the weights previously shown.

C2. Emission coefficients by region (2012-2018), before weighting

Unit: tCO_2/ kWh	Hokkaido	Tohoku	Tokyo	Chubu	Hokuriku	Kansai	Chugoku	Shikoku	Kyushu
2012	6.80E-04	5.60E-04	4.06E-04	3.73E-04	4.94E-04	4.75E-04	6.72E-04	6.56E-04	5.99E-04

2013	6.81E-04	5.89E-04	5.22E-04	5.09E-04	6.28E-04	5.16E-04	7.17E-04	7.06E-04	6.17E-04
2014	6.88E-04	5.73E-04	4.96E-04	4.94E-04	6.40E-04	5.23E-04	7.09E-04	6.88E-04	5.98E-04
2015	6.76E-04	5.59E-04	4.91E-04	4.82E-04	6.15E-04	4.96E-04	7.00E-04	6.69E-04	5.28E-04
2016	6.40E-04	5.48E-04	4.74E-04	4.80E-04	6.24E-04	4.93E-04	6.94E-04	5.29E-04	4.83E-04
2017	6.78E-04	5.23E-04	4.62E-04	4.72E-04	5.74E-04	4.18E-04	6.77E-04	5.35E-04	4.63E-04
2018	6.56E-04	5.28E-04	4.55E-04	4.52E-04	5.26E-04	3.34E-04	6.36E-04	5.28E-04	3.47E-04

Source of data: Ministry of Environment, 2023[20]. Each published document uses actual emission values from 2 years prior. In this study, we actual emission values retrieved using a 2-year lag. For instance, emission for the year 2012 is retrieved from the report from year 2014.

Step 3 consists in using the weighted average of dependent variables obtained in Step 1, and multiplying them with our estimated coefficients to obtain the converted values.

[i] Available from Ministry of Environment. (2021). Calculation Method - Overview of Emission Coefficients [Santei Houhou. Haishutu Keisuu Ichiran 算定方法・排出係数一覧]. Retrieved from https://ghg-santeikohyo.env.go.jp/calc

[20] https://ghg-santeikohyo.env.go.jp/calc